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PROCESS DESIGN MANUAL FOR CARBON ADSORPTION

ENVIRONMENTAL PROTECTION AGENCY

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PROCESS DESIGN MANUAL
FOR
CARBON ADSORPTION

U. S. ENVIRONMENTAL PROTECTION AGENCY
Technology Transfer

October 1973

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NOTICE

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ABSTRACT

The use of activated carbon for removal of dissolved organics from water and wastewater has long since been demonstrated to be feasible. In fact, it is one of the most efficient organic removal processes available to the engineer. The increasing need for highly polished effluents from wastewater treatment plants, necessary to accommodate the stringent requirements for both surface water quality and water reuse, has stimulated great interest in carbon treatment systems. Both the great capability for organic removal and the overall flexibility of the carbon adsorption process have encouraged its application in a variety of situations. It readily lends itself to integration into larger, more comprehensive waste treatment systems.

Activated carbon adsorbs a great variety of dissolved organic materials including many which are nonbiodegradable. Adsorption is facilitated by the large surface areas on the carbon granules which are attributable to its highly porous structure. Biological degradation occurring on the granules complements the adsorption process in removing dissolved organic material. Carbon in certain configurations also functions as a filter. The greatest cost within the carbon treatment process is the cost of the carbon itself. Thermal regeneration of the spent carbon makes the process economically feasible; the cost of the regenerating equipment, however, represents only a small fraction of the total capital equipment cost.

The most important design parameter is contact time. Hydraulic loading, within the ranges normally used, has little effect on adsorption. The basic process configurations of the physical plant include upflow or downflow, either under force of gravity or pump pressure, with fixed or moving beds, and single (parallel) or multi-stage (series) arrangement.

Data from both pilot and laboratory tests, as well as experience from existing full-scale plants, must be carefully interpreted prior to the design of a new plant. Procedures for preliminary tests are discussed here, and the characteristics of some full-scale plants, planned or operating, are presented as well for illustrative purposes.

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FOREWORD

The formation of the United States Environmental Protection Agency marked a new era of environmental awareness in America. This Agency's goals are national in scope and encompass broad responsibility in the area of air and water pollution, solid wastes, pesticides, and radiation. A vital part of EPA's national water pollution control effort is the constant development and dissemination of new technology for wastewater treatment.

It is now clear that only the most effective design and operation of wastewater treatment facilities, using the latest available techniques, will be adequate to meet the future water quality objectives and to ensure continued protection of the nation's waters. It is essential that this new technology be incorporated into the contemporary design of waste treatment facilities to achieve maximum benefit of our pollution control expenditures.

The purpose of this manual is to provide the engineering community and related industry a new source of information to be used in the planning, design and operation of present and future wastewater treatment facilities. It is recognized that there are a number of design manuals, manuals of standard practice, and design guidelines currently available in the field that adequately describe and interpret current engineering practices as related to traditional plant design. It is the intent of this manual to supplement this existing body of knowledge by describing new treatment methods, and by discussing the application of new techniques for more effectively removing a broad spectrum of contaminants from wastewater.

Much of the information presented is based on the evaluation and operation of pilot, demonstration and full-scale plants. The design criteria thus generated represent typical values. These values should be used as a guide and should be tempered with sound engineering judgment based on a complete analysis of the specific application.

This manual is one of several available through the Technology Transfer Office of EPA to describe recent technological advances and new information. This particular manual was initially issued in October of 1971 and this edition represents the first revision to the basic text. Future editions will be issued as warranted by advancing state-of-the-art to include new data as it becomes available, and to revise design criteria as additional full-scale operational information is generated.

CHAPTER 1

INTRODUCTION

1.1 Purpose

In the thrust to cleanup and improve the nation's waters, much effort, time, and money has been expended in the research and development of improved wastewater treatment methods and processes. This work has been aimed at producing processes and systems that will increase reliability and effectiveness of both existing wastewater treatment facilities and developing totally new systems to be planned and constructed in the future.

One system which has been demonstrated to be capable of providing dependable and efficient treatment and high quality effluents is granular activated carbon adsorption.

The purpose of this manual is to present information on design considerations and descriptions of existing and planned applications of granular activated carbon adsorption in the treatment of wastewaters.

1.2 Scope

This manual discusses and reviews activated carbon adsorption principles, pilot plant techniques, general and detailed process design considerations, costs, operational requirements, and describes existing or planned facilities.

This manual does not cover in detail wastewater treatment processes which normally precede or follow carbon adsorption, except to note the extent to which these processes affect the carbon adsorption system. Information in this manual pertains to the application of granular activated carbon systems to municipal wastewater treatment, as opposed to powdered carbon systems, because the experience with granular carbon adsorption and regeneration systems is greater than with the emerging powdered carbon technology.

Cost information has been compiled and estimates have been prepared for major individual unit processes and for various overall treatment systems. Where available, cost information has also been included for facilities in actual operation. Transferring overall system cost information to new locations must be done cautiously, since individual differences can strongly influence costs for a particular project.

This manual discusses the application of granular activated carbon adsorption both as a tertiary treatment process following conventional biological treatment systems, and as a unit process which may be applied to raw or primary treated wastewaters in physical-chemical treatment systems.

In its initial applications, granular carbon adsorption was used in "tertiary" stages for removal of additional organics from the effluent streams of conventional biological treatment systems. Granular carbon adsorption is now also being used as a second stage process in independent physical-chemical treatment (PCT) plants, since activated carbon can remove biodegradable as well as refractory organics. In the present context, physical-chemical treatment (PCT) refers to chemical coagulation and precipitation of raw municipal and/or industrial wastewater, followed by adsorption on activated carbon for removal of soluble and insoluble impurities.

At present, available data suggest that the effluent quality, cost, and reliability of PCT for soluble organic removal falls in between the results obtainable with conventional biological secondary treatment and "tertiary" carbon adsorption of biological secondary effluent.

The efficiency of PCT for removal of phosphorus, heavy metals, and suspended solids is substantially better than that of biological treatment systems and may approach that achievable with tertiary systems.

1.3 History

The use of carbon for purposes other than fuel has been reported as early as 1550 B. C. when it was used for medicinal purposes. The discovery of the phenomenon of adsorption, as now understood, is generally attributed to Scheele, who in 1773 described experiments on gases exposed to carbon. The earliest documented use of carbon for removal of impurities from solutions is 1785 when Lowitz observed that charcoal would decolorize many liquids. The first industrial application came a few years later when wood char was used in a refinery to clarify cane sugar. In the 1860's charcoal was used to remove tastes and odors from several municipal water supplies in England. However, it has only been in the last 50 years that the techniques of enhancing the adsorptive powers of charcoal through "activation" have been developed to a high degree on a scientific basis.

During World War I, the purification capabilities of activated carbon were demonstrated. A notable advance in the art was made during World War II with the development of the catalytically active carbons used for military gas masks. Since that time, activated carbon has been widely used as a process for separation and purification. Activated carbon is routinely used in the food, pharmaceutical, petroleum, chemical and water processing industries.

1.4 System Performance and Effluent Qualities

The performance and effluent quality obtainable from granular carbon treatment depends on the character of the wastewater being treated and the proficiency with which the facilities are operated. Due to these variations, it is impossible to present predictions of

TABLE 1–1

ANTICIPATED PERFORMANCE OF VARIOUS UNIT PROCESS COMBINATIONS

(FROM REFERENCE 1)

SOURCE OF WASTEWATER FLOW	ADDITIONAL UNIT PROCESS COMBINATIONS(1)	ESTIMATED PROCESS EFFLUENT QUALITY						
		BOD (mg/l)	COD (mg/l)	TURB. (JTU)	PO4 (mg/l)	S.S. (mg/l)	COLOR (UNITS)	NH_3 - N (mg/l)
Preliminary(2)	C,S	50-100	80-180	5-20	2-4	10-30	30-60	20-30
	C,S, F	30-70	50-150	1-2	0.5-2	2-4	30-60	20-30
	C,S, F, AC	5-10	25-45	1-2	0.5-2	2-4	5-20	20-30
	C,S, NS, F, AC	5-10	25-45	1-2	0.5-2	2-4	5-20	1-10
Primary Settling Effluent	C,S	50-100	80-180	5-15	2-4	10-25	30-60	20-30
	C,S, F	30-70	50-150	1-2	0.5-2	2-4	30-60	20-30
	C,S, F, AC	5-10	25-45	1-2	0.5-2	2-4	5-20	20-30
	C,S, NS, F, AC	5-10	25-45	1-2	0.5-2	2-4	5-20	1-10
High Rate Trickling Filter System Effluent	F	10-20	35-60	6-15	20-30	10-20	30-45	20-30
	C,S	10-15	35-55	2-9	1-3	4-12	25-40	20-30
	C,S, F	7-12	30-50	0.1-1	0.1-1	0-1	25-40	20-30
	C,S, F, AC	1-2	10-25	0.1-1	0.1-1	0-1	0-15	20-30
	C,S, NS, F, AC	1-2	10-25	0.1-1	0.1-1	0-1	0-15	1-10
Conventional Activated Sludge System Effluent	F	3-7	30-50	2-8	20-30	3-12	25-50	20-30
	C,S	3-7	30-50	2-7	1-3	3-10	20-40	20-30
	C,S, F	1-2	25-45	0.1-1	0.1-1	0-1	20-40	20-30
	C,S, F, AC	0-1	5-15	0.1-1	0.1-1	0-1	0-15	20-30
	C,S, NS, F, AC	0-1	5-15	0.1-1	0.1-1	0-1	0-15	1-10

(1) C,S = coagulation and sedimentation; F = mixed-media filtration;
AC = activated carbon adsorption; NS = ammonia stripping.
Lower effluent NH_3 value at 18°C; upper value at 13°C.

(2) Preliminary treatment — grit removal, screen chamber.

effluent quality of various unit process combinations which would be universally applicable. However, a general indication of expected trends and relative performances is presented in Table 1-1.

1.5 Additional Reading

1. Mattson, J. S. and Mark, H. B. Jr., *Activated Carbon.* Marcel Dekker, New York, 1971.

2. Smisek, M., and Cerny, S., *Active Carbon.* Elsevier Publishing Co., New York, 1970.

3. *Adsorption from Aqueous Solutions.* Symposium Proceedings, Advances in Chemistry Series, 79, American Chemical Society, Washington, D. C., 1968.

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1. Culp, R. L., and Culp, G. L., *Advanced Wastewater Treatment.* Van Nostrand Reinhold, New York, 1971.

CHAPTER 2

ACTIVATED CARBON MANUFACTURE AND CHARACTERISTICS

2.1 Activated Carbon–Introduction

Activated carbon removes organic contaminants from water by the process of adsorption or the attraction and accumulation of one substance on the surface of another. In general, high surface area and pore structure are the prime considerations in adsorption or organics from water; whereas, the chemical nature of the carbon surface is of relatively minor significance. Granular activated carbons typically have surface areas of 500-1,400 square meters per gram. Activated carbon has a preference for organic compounds and, because of this selectivity, is particularly effective in removing organic compounds from aqueous solution.

Much of the surface area available for adsorption in granular carbon particles is found in the pores within the granular carbon particles created during the activation process. The major contribution to surface area is located in pores of molecular dimensions. A molecule will not readily penetrate into a pore smaller than a certain critical diameter and will be excluded from pores smaller than this diameter.

The most tenacious adsorption takes place when the pores are barely large enough to admit the adsorbing molecules. The smaller the pores with respect to the molecules, the greater the forces of attraction.

Activated carbons can be made from a variety of carbonaceous materials including wood, coal, peat, lignin, nut shells, bagasse (sugar cane pulp), sawdust, lignite, bone, and petroleum residues. In the past, carbons used in industrial applications have been produced most frequently from wood, peat, and wastes of vegetable origin such as fruit stones, nut shells and sawdust. The present tendency in wastewater treatment applications, however, is toward use of various kinds of natural coal and coke which are relatively inexpensive and readily available. Of interest is the potential utilization of different wastes as raw materials; for example: waste lignin, sulfite liquors, processing wastes from petroleum and lubricating oils, and carbonaceous solid waste.

The quality of the resulting activated carbon is influenced by the starting material. The starting material is particularly important where selective adsorptive properties are required, as, for example, in the treatment of wine, or in the separation of components in preparative chemistry. For most activated carbons, however, some properties arising from the nature of the starting material are masked by choice of production technique. These production techniques can form granular activated carbons by crushing or pressing. Crushed activated carbon is prepared by activating a lump material, which is then crushed and classified to desired particle size. Pressed activated carbon is formed prior to activation. The appropriate starting material is prepared in a plastic mass, then extruded from a die and cut into pieces of uniform length. These uniform cylindrical shapes are then activated. The necessary hardness is acquired in the activation process.

The physical characteristics of hardness, a very important factor, are directly related to the nature of the starting material for crushed activated carbons. For activated carbons formed from pulverized materials, which are then bound together, the nature of the binding agent is a major factor in determining the hardness of the finished product.

2.2 The Activation Process

Activated carbon is manufactured by a process consisting of raw material dehydration and carbonization followed by activation. The starting material is dehydrated and carbonized by slowly heating in the absence of air, sometimes using a dehydrating agent such as zinc chloride or phosphoric acid. Excess water, including structural water, must be driven from the organic material. Carbonization converts this organic material to primary carbon, which is a mixture of ash (inert inorganics), tars, amorphous carbon, and crystalline carbon (elementary graphitic crystallites). Non-carbon elements (H_2 and O_2) are removed in gaseous form and the freed elementary carbon atoms are grouped into oxidized crystallographic formations. [1] During carbonization, some decomposition products or tars will be deposited in the pores, but will be removed in the activation step.

Activation is essentially a two-phase process requiring burn-off of amorphous decomposition products (tars), plus enlargement of pores in the carbonized material. Burn-off frees the pore openings, increasing the number of pores, and activation enlarges these pore openings. Activated carbon can be manufactured by two different procedures: physical activation and chemical activation. Although both processes are widely used, physically activated carbons are utilized in wastewater treatment while chemically activated carbons are utilized elsewhere–such as the recovery of solvents. The discussion of carbon activation herein is therefore limited to physical activation.

Carbonization and activation are two separate processes. The methods of carbonization differ, and the method used will affect activation and the final quality of the carbon. The essential steps in carbonization are as follows:

1. Dry the raw material at temperatures up to 170 degrees C.

2. Heat the dried material above 170 degrees C causing degradation with evolution of CO, CO_2 and acetic acid.

3. Exothermal decomposition of the material at temperatures of 270-280 degrees C with formation of considerable amounts of tar, methanol and other by-products.

4. Complete the carbonization process at a temperature of 400-600 degrees C, with a yield of approximately 80 percent primary carbon.

The carbonized intermediate product is then treated with an activating agent such as steam or carbon dioxide (steam is most widely used). Steam, at temperatures of 750-950 degrees C, burns off the decomposition products exposing pore openings for subsequent enlargement. All pores are not plugged with amorphous carbon, therefore some pores are exposed to the activating agent for longer periods of time. Exposure to the activating agent results in the widening of existing pores, and development of the macroporous structure.

2.3 The Nature of Adsorption

Adsorption by activated carbon involves the accumulation or concentration of substances at a surface or interface. Adsorption is a process in which matter is extracted from one phase and concentrated at the surface of another, and is therefore termed a surface phenomenon. Adsorption from wastewater onto activated carbon can occur as a result of two separate properties of the wastewater-activated carbon system, or some combination of the two: (1) the low solubility of a particular solute in the wastewater; and (2) a high affinity of a particular solute in the wastewater for the activated carbon. According to the most generally accepted concepts of adsorption, this latter surface phenomenon may be predominantly one of electrical attraction of the solute to the carbon, of van der Waals attraction, or of a chemical nature.

There are essentially three consecutive steps in the adsorption of dissolved materials in wastewater by granular activated carbon. The first step is the transport of the solute through a surface film to the exterior of the carbon. The second step is the diffusion of the solute within the pores of the activated carbon. The third and final step is adsorption of the solute on the interior surfaces bounding the pore and capillary spaces of the activated carbon.

There are several factors which can influence adsorption by activated carbon, including: (1) the nature of the carbon itself; (2) the nature of the material to be adsorbed, including its molecular size and polarity; (3) the nature of the solution, including its pH; and (4) the contacting system and its mode of operation.

This topic is considered in more detail elsewhere [1, 2, 3, 4].

2.4 Carbon Properties Relating to Adsorption

Because adsorption is a surface phenomenon, the ability of activated carbon to adsorb large quantities of organic molecules from solution stems from its highly porous structure, which provides a large surface area. Carbon has been activated with a surface area yield of some 2,500 m^2/gram, but 1,000 m^2/gram is more typical.

Total surface area is normally measured by the adsorption of nitrogen gas by the Brunauer-Emmett-Teller (BET) method [5]. The distribution of this area into pores of different diameters is measured by determining the amount of nitrogen desorbed at intermediate pressures.

Another method for determining the area of pores above a lower size limit for a given carbon is by measuring the amount of adsorbate of a given molecular size that is removed from solution. For example, the amount of iodine adsorbed from solution has been found to be proportional to the surface area contributed by pores having diameters greater than 10 angstroms. Similarly, the adsorption of methylene blue and molasses can be correlated with surface area in pores with diameters greater than 15 and 28 angstroms, respectively.

Particle size is generally considered to affect adsorption rate, but not adsorptive capacity. The external surface constitutes a small percent of the total surface area of an activated carbon particle. Since adsorption capacity is related to surface area, a given weight of carbon gains little adsorptive capacity upon being crushed to smaller size.

2.5 Carbon Particle Size

Activated carbons are classified according to their form: for example, powdered or granular; and according to their use: for example, water or wastewater purification, sugar decolorizing, and liquid or gas phase solvent extraction. Granular carbons are those which are larger than approximately U. S Sieve Series No. 50, while powdered carbons are those which are smaller. Properties of several commercially available granular carbons are presented in Table 2-1.

Headloss in the carbon contactor is an important design consideration and is affected by the carbon particle size. The suspended solids concentration in the wastewater to be treated by the carbon will also affect the headloss and will thereby be a factor in selection of carbon particle size. The particle size headloss design considerations are discussed in detail in Chapter 3.

2.6 Adsorption Characteristics

The adsorptive capacity of a carbon can be measured by determining the adsorption isotherm with the wastewater under consideration. Simpler adsorption capacity tests such as the Iodine Number or the Molasses Number may also be appropriate. Pilot tests are also considered important. These tests are described in detail in the chapter on laboratory and pilot tests (Chapter 4).

TABLE 2–1

PROPERTIES OF SEVERAL COMMERCIALLY AVAILABLE CARBONS*

	ICI AMERICA HYDRODARCO 3000	CALGON FILTRASORB 300 (8x30)	WESTVACO NUCHAR WV-L (8x30)	WITCO 517 (12x30)
PHYSICAL PROPERTIES				
Surface area, m^2/gm (BET)	600-650	950-1050	1000	1050
Apparent density, gm/cc	0.43	0.48	0.48	0.48
Density, backwashed and drained, lb/cu.ft.	22	26	26	30
Real density, gm/cc	2.0	2.1	2.1	2.1
Particle density, gm/cc	1.4–1.5	1.3–1.4	1.4	0.92
Effective size, mm	0.8–0.9	0.8–0.9	0.85–1.05	0.89
Uniformity coefficient	1.7	1.9 or less	1.8 or less	1.44
Pore volume, cc/gm	0.95	0.85	0.85	0.60
Mean particle diameter, mm	1.6	1.5–1.7	1.5–1.7	1.2
SPECIFICATIONS				
Sieve size (U.S. std. series)				
Larger than No. 8 (max. %)	8	8	8	–
Larger than No. 12 (max. %)	–	–	–	5
Smaller than No. 30 (max. %)	5	5	5	5
Smaller than No. 40 (max. %)	–	–	–	–
Iodine No.	650	900	950	1000
Abrasion No., minimum	**	70	70	85
Ash (%)	**	8	7.5	0.5
Moisture as packed (max. %)	**	2	2	1

* Other sizes of carbon are available on request from the manufacturers.

** No available data from the manufacturer.

– Not applicable to this size carbon.

2.7 References

1. Weber, W. J., Jr., *Physicochemical Processes for Water Quality Control.* John Wiley and Sons, Inc., New York, 1972.

2. Hassler, J. W., *Activated Carbon.* Chemical Publishing Co., 1963.

3. DeBoer, J. H. *The Dynamic Character of Adsorption.* Oxford University Press, 1968.

4. Mantell, C. L., *Adsorption.* McGraw-Hill Book Co., 1945.

5. Smisek, M., and Cerny, S., *Active Carbon.* Elsevier Publishing Co., New York, 1970.

CHAPTER 3

GENERAL PROCESS DESIGN CONSIDERATIONS

3.1 Introduction

Activated carbon has been utilized in numerous industrial products and processes for many years, and much of the present application technology has developed therefrom. In the last ten years, granular activated carbon treatment of wastewater has been demonstrated for both municipal and industrial applications. The process has become much more attractive for widespread use due to the development of economical regeneration methods and equipment.

There are currently two approaches for the use of granular activated carbon in wastewater treatment. One approach is to use activated carbon in a "tertiary" treatment sequence following conventional primary and biological secondary treatment. Tertiary treatment processes involving carbon range from treatment of the secondary effluent with only activated carbon to systems with chemical clarification , nutrient removal, filtration, carbon adsorption and disinfection. Another approach utilizes activated carbon in a "physical-chemical" treatment (PCT) process in which raw wastewater is treated in a primary clarifer with chemicals prior to carbon adsorption. Filtration and disinfection may also be included in PCT, but biological processes are not used. Flow diagrams for some alternate treatment schemes for tertiary and PCT systems are shown in Figures 3-1 and 3-2. A detailed description of tertiary and PCT systems currently under design, construction, or in operation is included in Chapter 6.

If biological treatment and efficient filtration precede carbon treatment, there are several benefits: (1) the applied loads of BOD, COD, and other organics are reduced allowing either the production of a higher quality carbon column effluent at a given contact time, or the production of equal water quality at a shorter contact period, (2) the applied loads of suspended and colloidal solids are less, thus reducing headloss through the bed of carbon, which may aid in solving problems of physical plugging, ash buildup, and progressive loss of adsorptive capacity in the carbon particles after several cycles of regeneration, and (3) the problems of biological growth, septicity, and hydrogen sulfide production may be decreased by reducing the supply of bacterial food and oxygen demanding substances applied to the carbon.

The PCT approach seeks to make maximum use of granular activated carbon by extending its function of removing refractory dissolved organics to adsorption of biodegradable organics as well, and, in some cases, by using the granular bed of carbon as a filter to remove suspended and colloidal materials. With this approach the carbon is loaded as heavily as possible within the limits of effluent water quality criteria. PCT will result in capital cost savings when compared with biological treatment followed by

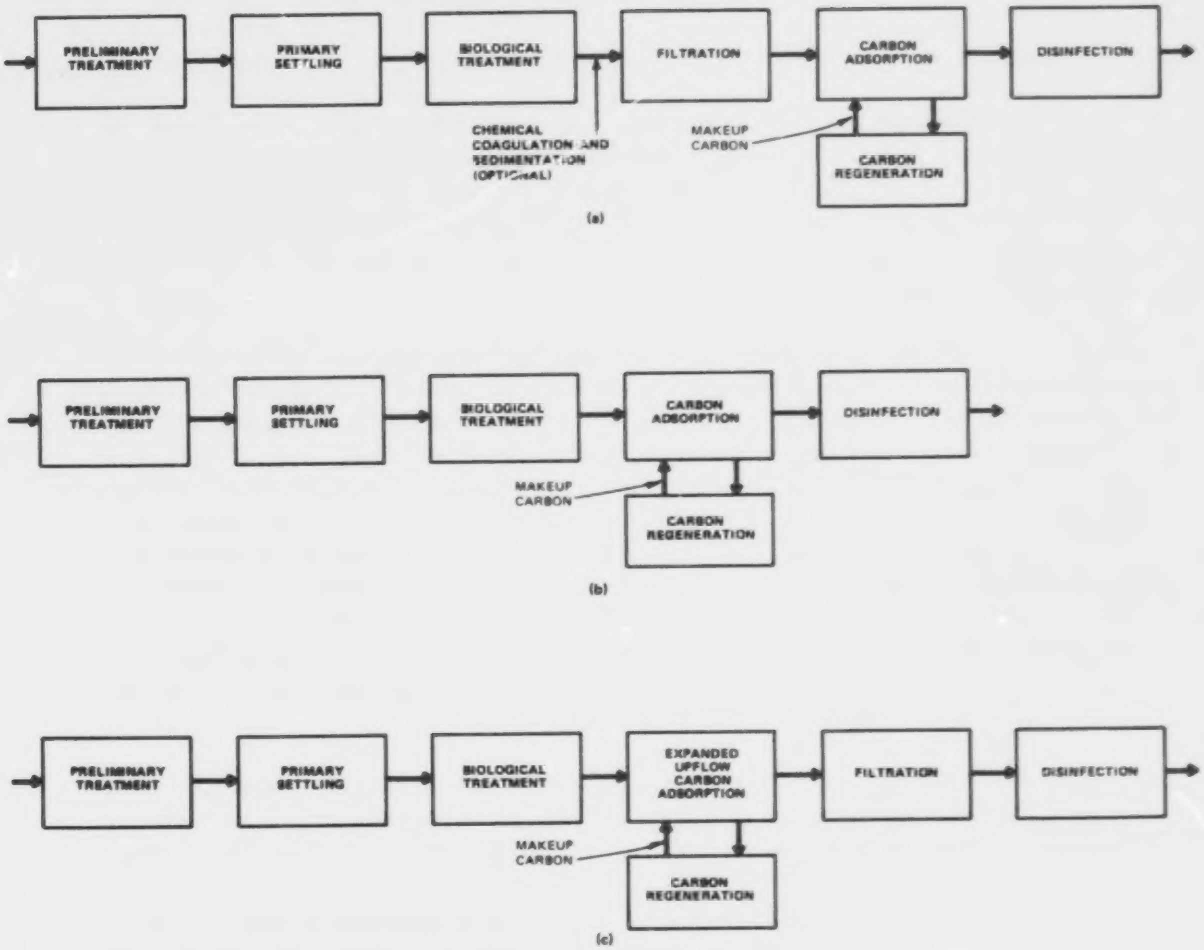

PRELIMINARY TREATMENT
PRIMARY SETTLING
BIOLOGICAL TREATMENT
FILTRATION
CARBON ADSORPTION
DISINFECTION
CHEMICAL COAGULATION AND SEDIMENTATION (OPTIONAL)
MAKEUP CARBON
CARBON REGENERATION
(a)
PRELIMINARY TREATMENT
PRIMARY SETTLING
BIOLOGICAL TREATMENT
CARBON ADSORPTION
DISINFECTION
MAKEUP CARBON
CARBON REGENERATION
(b)
PRELIMINARY TREATMENT
PRIMARY SETTLING
BIOLOGICAL TREATMENT
EXPANDED UPFLOW CARBON ADSORPTION
FILTRATION
DISINFECTION
MAKEUP CARBON
CARBON REGENERATION
(c)

FIGURE 3–1

TYPICAL TREATMENT SCHEMES UTILIZING CARBON ADSORPTION AS A TERTIARY STEP

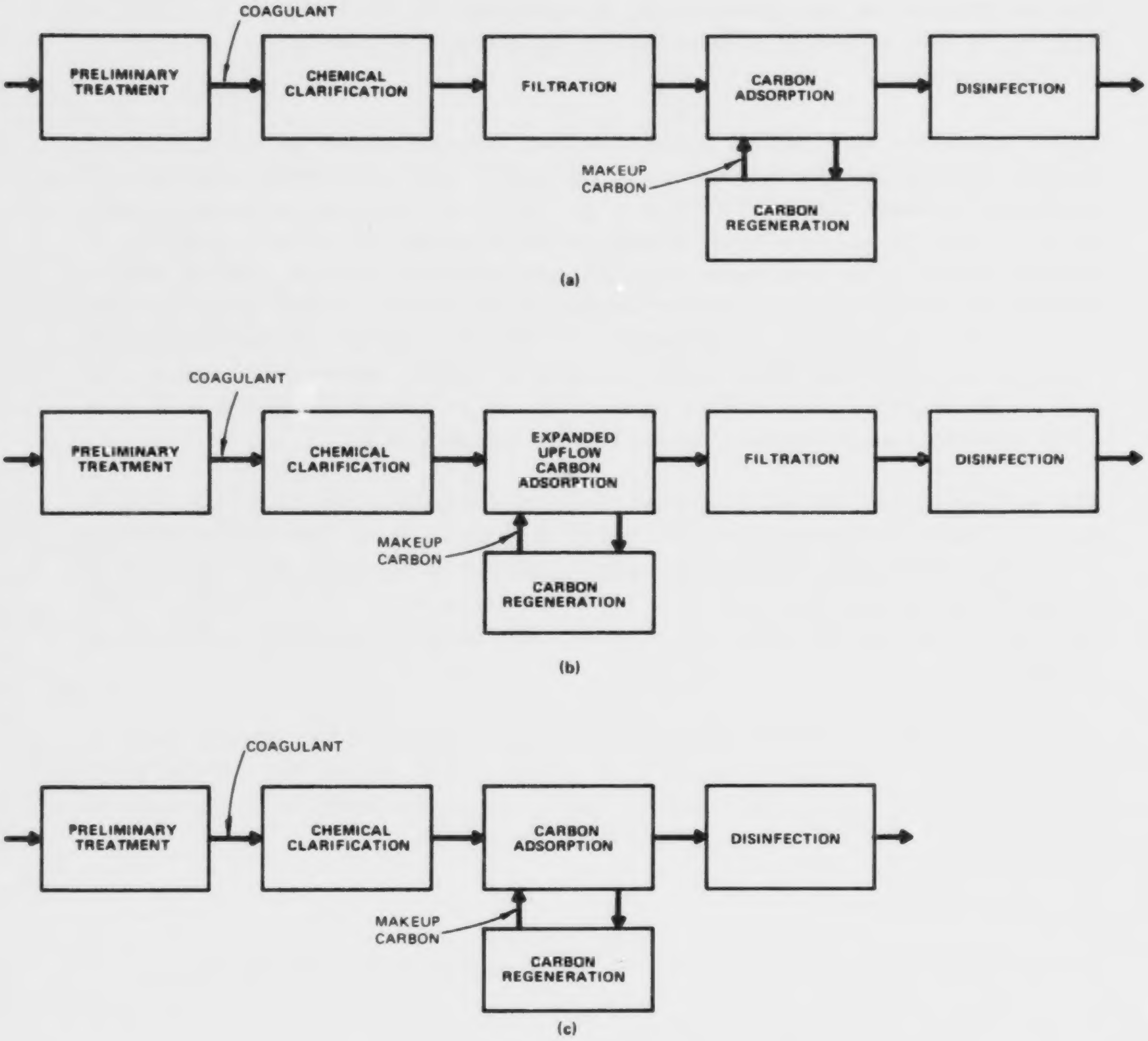

COAGULANT
PRELIMINARY TREATMENT
CHEMICAL CLARIFICATION
FILTRATION
CARBON ADSORPTION
DISINFECTION
MAKEUP CARBON
CARBON REGENERATION
(a)
COAGULANT
PRELIMINARY TREATMENT
CHEMICAL CLARIFICATION
EXPANDED UPFLOW CARBON ADSORPTION
FILTRATION
DISINFECTION
MAKEUP CARBON
CARBON REGENERATION
(b)
COAGULANT
PRELIMINARY TREATMENT
CHEMICAL CLARIFICATION
CARBON ADSORPTION
DISINFECTION
MAKEUP CARBON
CARBON REGENERATION
(c)

FIGURE 3–2

TYPICAL PHYSICAL–CHEMICAL TREATMENT SCHEMES tertiary treatment. However, it has been shown in several cases that only when biological oxidation, chemical coagulation, filtration, and adsorption are operated in series as separate processes can the effluent quality be optimized. The capabilities of PCT must be evaluated in light of specific effluent quality requirements to determine its applicability to a given problem.

Carbon adsorption and carbon regeneration are basically simple processes, and are therefore quite reliable. Carbon is versatile and may be used in a variety of locations in wastewater treatment plants. There is no single method of contacting or contactor design which is best for all conditions because of the placement of carbon adsorption at different points in the wastewater treatment unit operation sequence, and the varying qualities of wastewater which may be applied to the carbon. Design, equipment, and material selection may also be influenced by the total capacity of the plant under consideration. There are fewer design variables in carbon regeneration systems, and facilities are therefore more uniform in their concept and design. Also, somewhat more standardized are carbon transport, monitoring, and control systems.

With the requirement for more complete wastewater treatment there also is a need for greater reliability of unit processes and overall treatment systems. The ability of carbon to continue functioning satisfactorily under certain shock hydraulic and organic loads contributes to its reliability. The need for standby facilities to assure continuous plant operation at full capacity under various service and emergency conditions should not be overlooked.

This chapter presents information intended to assist engineers in the detailed design of granular carbon contacting and regeneration systems and auxiliaries. This information is drawn from theory and the experience gained from the design and operation of laboratory, pilot, and full-scale carbon treatment systems.

3.2 Design Flow

Selection of the proper design flow also requires an analysis of the following factors:

1. Useful operating life of the plant
    a. as influenced by normal wear-and-tear.
    b. as influenced by technology.
2. Interest rates and the rate of inflation during the life of the plant.
3. Expected population changes in the plant service area.

4. Changes in domestic living habits and consumer patterns (i.e., standard of living).

5. Changes in levels and types of industrial activity in the plant's service area.

6. Recycle flows within the plant (which may amount to 5 to 25 percent of the plant raw flow).

7. Changes in requirements for treated water quality.

One approach is to design the facility for a relatively short term, taking into account only those future events and trends which can be foreseen with some certainty. At the same time, the plant should be constructed so that its capacity can be increased as needed without abandoning or greatly changing the original equipment. A good way to accomplish this is by using the modular approach to plant design which provides for plant expansion by building new plant units (or modules). Physical-chemical treatment plants, and the carbon facilities in particular, are well-suited to the modular design approach.

Additional capacity for removal of organics can be provided by adding extra spent carbon storage capacity and by oversizing the regeneration facilities. In the original design, it is often relatively inexpensive to oversize the regeneration equipment and to operate it initially on a part-time schedule. Application of more organics to the carbon will increase the quantity of carbon to be regenerated; however, there are some savings resulting from continuous rather than intermittent operation of the furnace. Thus, nonproductive operating costs, such as that associated with startup and shutdown, will be reduced but will be offset by productive operating costs.

Since carbon adsorbers readily conform to modular design concepts, treatment plant capacity may be increased by merely adding additional contactor vessels, as required. The initial facility layout should anticipate future installation of additional contactors and associated apparatus in order to minimize construction costs and disruption of plant operations.

Streams of wastewater vary in their volume and chemical composition because of changes in the processes or in the events which generate these streams. These variations frequently exhibit clearly defined cycles. Municipal wastewater exhibits diurnal cycles corresponding to the life patterns of the population, length of sewer, and size of the town. Infiltration of ground water or storm water connections may have a marked effect on these cycles. Industrial wastes may be influenced by the working hours of the plants, shift changes, weekend shutdowns, summer holidays, or fluctuations in production rates caused by seasonal marketing patterns. It is important to recognize that fluctuations occur in the chemical character of the wastewater as well as in its volume.

Provisions must be included in treatment plant design to handle these variations. In the past, the major elements in a conventional plant usually have been designed on the basis of the average dry weather flow expected at the end of the design period, although plant hydraulics may have been designed on the basis of peak hourly flows. In cases of greater-than-average flow, wastewater has often been permitted to pass through the treatment plant as usual. The increased flow often results in poorer treatment, and an effluent of poor quality may be discharged for a time during the high flow period.

One method of avoiding inferior effluent quality is to construct a flow equalization basin preceding the plant. Excess flows or highly concentrated wastes can then be accumulated during surges and later be allowed to enter the plant gradually without impairing treatment efficiency. Some form of flow equalization may be advisable in any situation where the processes themselves cannot readily accommodate the flow variations, or where it is not economical to provide larger or standby units for the greater capacity requirement. A detailed discussion of flow equalization facilities is presented in the U. S. EPA Technology Transfer Process Design Manual for Upgrading Existing Wastewater Treatment Plants.

Equalization of the wastewater flow has the following advantages:

1. The head and flow capacity of pump systems can be reduced with savings in capital investment and the cost of electric power for operation.

2. The total head for operation of gravity flow units can be reduced for the lower flow rate, thus decreasing construction costs.

3. Lower flow rates will allow the use of smaller pipelines, valves, and meters; and the reduced span of instrument operating ranges may increase their sensitivity and control capability.

4. Carbon contactors may be smaller or fewer in number without exceeding safe design criteria.

3.3 Wastewater Quality Considerations

Wastewater quality parameters of concern in activated carbon treatment systems include suspended solids, oxygen demand as measured by BOD, COD or TOC, other organics such as MBAS, or phenol,and dissolved oxygen. If there are effluent requirements for any or all of these parameters, then much of the design criteria must be established by laboratory and bench scale tests as described in Chapter 4.

3.4 Carbon Contacting Systems

The alternatives for carbon contacting systems include:

1. Downflow or upflow of the wastewater through the carbon bed.
2. Series or parallel operation (single or multi-stage).
3. Pressure or gravity operation in downflow contactors.
4. Packed or expanded bed operation in upflow contactors.
5. Materials of construction and configuration of carbon vessel.
    a. Steel or concrete.
    b. Circular or rectangular cross-section.

3.4.1 Upflow versus Downflow Contacting Systems

Upflow beds have an advantage over downflow beds in the efficiency of carbon use because they can more closely approach continuous countercurrent contact operation. Countercurrent operation results in the minimum use of carbon, or the lowest carbon dosage rate. Upflow beds may be designed to allow addition of fresh carbon and withdrawal of spent carbon while the column remains in operation. When these operations are conducted almost continuously, the bed may be referred to as a pulsed bed. A pulsed bed may be either an upflow packed bed or an upflow expanded bed. Upflow packed beds require a high clarity influent (usually a turbidity less than about 2.5 JTU) which may be considered a disadvantage to their use. Upflow expanded beds have the advantages of being able to treat wastewater relatively high in suspended solids, and of being able to use finer carbon (which reduces the required contact time) without excessive headlosses. Where upflow packed beds typically use 8 x 30 mesh carbon, upflow expanded beds typically use 12 x 40 mesh.

The principal reason for using a downflow contactor is to use the carbon for two purposes: (1) adsorption of organics and (2) filtration of suspended materials. The principle advantage to the dual use of granular carbon is some reduction in capital cost. This economic gain is offset, to an extent not now fully predictable, by loss of efficiency in both filtration and adsorption, and perhaps also by higher operating costs. The sacrifice in finished water quality which results from combined adsorption-filtration by carbon may or may not be a factor depending upon the effluent quality required.

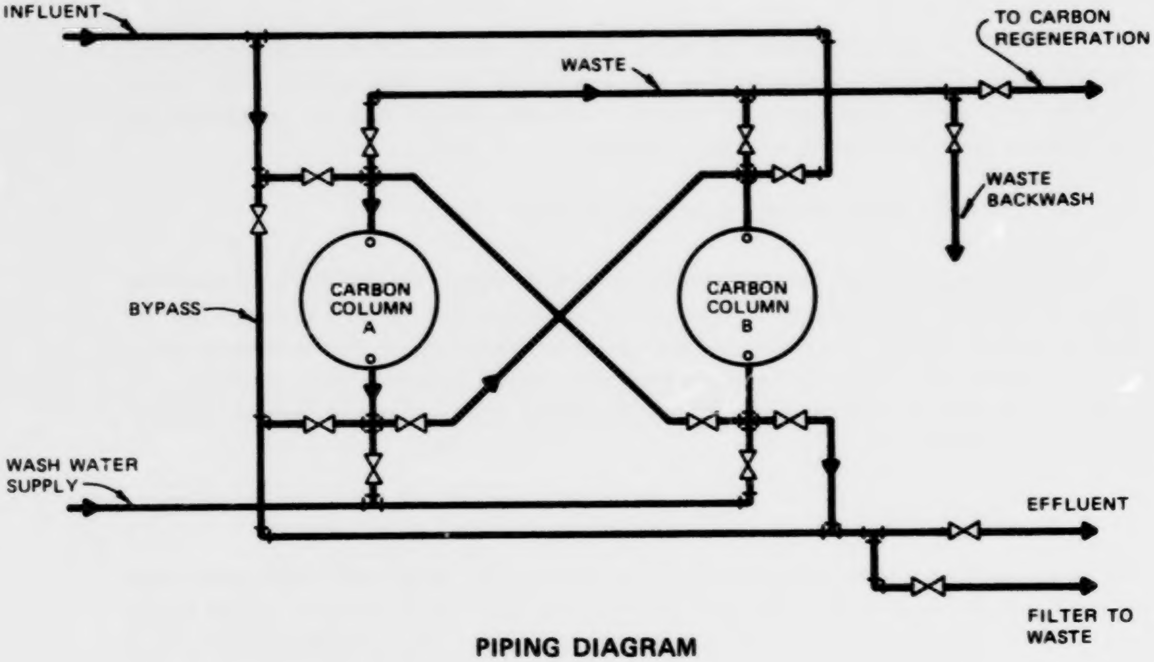
Downflow beds may be operated in parallel or in series (multi-stage). Valves and piping are provided in series installations to permit each bed to be operated in any position in the series sequence, thus giving a pseudo-countercurrent operation. More than two beds in series are seldom used because of the cost of required valves and piping.

Provision must be made to periodically and thoroughly backwash downflow beds to relieve the pressure drop associated with the accumulation of suspended solids. Continued operation of a downflow bed for several days without backwashing may compact or foul the bed sufficiently to make it more difficult to expand the bed during backwash without the use of an excessive quantity of backwash water, i.e., more than 5 percent of the product water. Upflow beds may be flushed through a simple well screen inlet-outlet system. Downflow beds require a false bottom support system, backwash facilities, and controls similar to those used in waterworks practice for sand filters.

Equipment available for automatic operation of filters is highly developed, reliable, and offers a satisfactory method of process control. Operation and control of upflow countercurrent carbon columns, following efficient filters, are best accomplished by simple, manual controls. Except for occasional flow reversal, valves serving separate carbon columns are usually operated only during withdrawal and replacement of carbon for regeneration, perhaps once every 4-6 weeks. Valve operation for this purpose is best done manually with operator attendance and observation, and is not amenable to reliable automatic control.

The use of downflow carbon contactors for the dual purposes of adsorption and filtration provides capital cost savings. However, the carbon filter-contactor is basically a surface-type filter, and, as such, is subject to the shortcomings of surface filters in processing sewage. Upsets in pretreatment which produce sudden increases in suspended solids or turbidity can completely blind the surface of a single media bed which requires backwashing before it can be restored to service. If the upset in applied water quality continues for an hour or two, then the supply of high-quality water necessary for backwashing carbon filter-contactors may be exhausted. Separate filters can be backwashed and placed back on line in 20 minutes or less. Backwashing a carbon filter-contactor may require longer and a proportionally larger volume of water of higher quality to avoid plugging the bottom of a deep bed and saturating it with adsorbed organics. Whether using upflow or downflow contactors, filters protect carbon columns from pretreatment upsets and increase the overall plant reliability.

The underdrain system used for downflow carbon beds is similar to that used for conventional water filters and will not be discussed in detail here. Figure 3-3 illustrates a two-bed series downflow system for carbon contact. As indicated, water is first passed down through Column A and then down through Column B. When the carbon in Column A is exhausted, the carbon in Column B is only partially spent. At this time, all carbon in Column A is removed for regeneration, and is replaced with fresh carbon. Column B


INFLUENT
TO CARBON REGENERATION
WASTE
WASTE BACKWASH
CARBON COLUMN A
CARBON COLUMN B
BYPASS
WASH WATER SUPPLY
EFFLUENT
FILTER TO WASTE

PIPING DIAGRAM

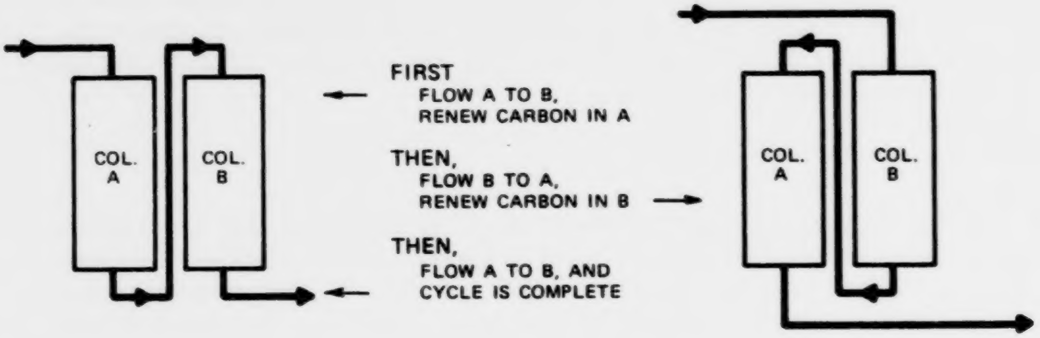

COL. A
COL. B
FIRST
FLOW A TO B,
RENEW CARBON IN A
THEN,
FLOW B TO A,
RENEW CARBON IN B
THEN,
FLOW A TO B, AND
CYCLE IS COMPLETE
COL. A
COL. B

FIGURE 3–3
TWO DOWNFLOW CARBON BEDS IN SERIES

then becomes the lead column in the series. When the carbon in Column B is exhausted, the carbon is removed for regeneration and is replaced with fresh carbon. With upflow columns, no spare contactors are needed, because carbon can be withdrawn for regeneration while the column remains in service.

3.4.2. Gravity versus Pressure Contacting Systems

The use of pressure vessels for carbon contactors will increase the flexibility of operation since it will allow the system to be operated at higher pressure losses. This may allow the carbon contact system to operate during upsets or variations in the wastewater flow. Gravity contactors may be more economical since concrete and common wall construction may be utilized. Examples for the design of both types of systems are given later in this chapter.

3.4.3 Aspect Ratios

The aspect ratio of a carbon column is the bed depth to diameter ratio. With good design of the flow distribution and collection systems, the aspect ratio is not a crucial factor, and ratios of even less than 1:1 are satisfactory. However, if the granular bed itself is to be used as a means of flow distribution, then high aspect ratios (greater than 4:1) are desirable to minimize short-circuiting and dead spots in the bed. The current trend in design is to provide inlet and outlet arrangements which distribute and collect the influent and effluent water very uniformly across the entire cross-section of the bed, in which case the aspect ratio is not important.

3.4.4 Number of Contactors

From a process reliability standpoint, there should be an adequate number of contactors (or pairs of contactors if series units are used) to provide adequate treatment even with one contactor (or pair of contactors) out of service for repairs. In large plants, this is not a constraint since the physical limitations on individual contactor's size dictate a large number of columns. Shop-assembled pressure vessels cannot be greater than 12 feet in diameter and 60 feet overall length and still be transportable. At 30 minutes contact, the maximum capacity per shop fabricated vessel is about 2 mgd with more typical designs (see Figure 3-8) corresponding to about 1 mgd per column.

Most open concrete contactors will have a maximum capacity of 2-4 mgd per contactor at 30 minutes contact, as the maximum area consistent with good flow distribution is about 1,000 square feet. Thus, for plants of 5 mgd and above, provision of enough contactors to insure plant reliability does not cause any added costs.

For small plants, it may be necessary to use two or more columns to provide flexibility of operation even though one larger column capable of handling the entire flow may be technically feasible. Some added carbon usage may be achieved by blending of the effluent from two columns. For example, with two columns in parallel and an effluent COD standard of 20 mg/l, the effluent COD from one column may be allowed to reach 25 mg/l if that from the other has reached only 15 mg/l, since the blended effluents still meet the requirement. Some operating cost savings may result from the slight additional carbon loading permitted by blending effluents from parallel columns if it is elected to operate the columns in the manner suggested above.

The relative economics for various number of contactors for a given situation is discussed in the literature [1] and this lengthy discussion will not be repeated here.

3.4.5 Flow Distribution and Collection Requirements and Other Contactor Functions

The functions to be carried out for efficient operation of carbon contactors are rather simple, but they are worthy of enumeration. The first is to provide contact between the water and the carbon grains for the proper length of time. This requires good distribution and collection of the water at the inlet and outlet of the carbon column, which is not too difficult, as any granular bed is, in itself, a good flow equalizer. The shape of the contacting portion of the vessel is not crucial if the water is properly distributed and collected. Of importance in pulsed upflow beds is the function of uniform withdrawal of spent carbon without mixing of partially spent carbon and without "rat-holing" the center portion of the carbon in the column. A 45 degree cone bottom with strategically located water jets is ideal for this function. In small tanks, a 60 degree cone bottom is preferable. Another function is placement of the makeup and regenerated carbon on the carbon in the column in a layer of uniform depth. In closed contactors, an inverted 45 degree cone serves the purpose very well. A dished top is cheaper, but the fresh carbon is deposited only in the center of the bed, and thus some carbon efficiency is lost. Another function is the separation of water and carbon at the inlet and outlet of the column. A stainless steel well screen serves this purpose very well in a closed contactor. For 8 x 30 mesh carbon, a screen opening of 0.020 inch has proved satisfactory.

In open contactors of a design similar to gravity filters, the backwash collection troughs should be covered with a screen to prevent loss of carbon during backwash.

3.4.6 Hydraulic Loading and Headloss Characteristics of Carbon Beds

The flow rate and bed depth necessary for optimum performance will depend upon the rate of adsorption of impurities from wastewater by the carbon. The general range of flow rates (or hydraulic loading) is 2-10 gpm/sq ft of cross-sectional area. Bed depths are usually 10-30 feet.

Both theoretical analysis and experimental data support the contention that there are critical velocities for liquids passing through porous beds which change the nature of the resistance to diffusion. At low velocities, the solute content of the stagnant film surrounding the adsorbent particles may become depleted more rapidly than the solute can be replaced by diffusion from the main body of the liquid. Thus, the diffusional resistance across the film is controlling. As the velocity is increased, the point will be reached where the controlling effect will be the inability of the adsorbent material to remove the solute from solution as rapidly as it is transported to the surface from the main body of the stream. Within the range of loadings of 2-10 gpm/sq ft, several studies have found that velocity is not a limiting factor.

Hydraulic loading has an additional effect on carbon column operation. Increasing flow rates through the carbon will cause increasing headlosses (ΔP). Headloss is dependent on the flow rate and carbon particle size. This relationship for clean water passing through a bed of clean carbon is expressed in the formula:

$$\Delta P = \frac{K \nu V L_c}{{D_p}^2 \cdot D_c}$$

where: ΔP = Pressure drop, inches
K = Constant
ν = Viscosity, centipoise
V = Flow rate, gpm
L_c = Bed depth, feet
D_p = Mean particle diameter, mm
D_c = Column diameter, inches

Hydraulic headloss is then related directly to flow rate and inversely related to particle size. Figure 3-4 illustrates the increasing pressure drop with increasing hydraulic loading for different sized carbons from different manufacturers, operated in a downflow mode. Because of the more favorable headloss characteristics, 8 x 30 mesh carbon is often preferred for downflow beds while 12 x 40 mesh carbon may be preferable for upflow beds because a lower upflow velocity is required for expansion.

The headloss for a given hydraulic loading with wastewater feed must be determined by pilot testing. Since headloss development is such an important consideration in the design of a carbon bed, hydraulic loading cannot be discussed in isolation from several other design factors. If an excessive rate of headloss development (due to a high hydraulic loading) is anticipated, an upflow bed should be given consideration. The choice of

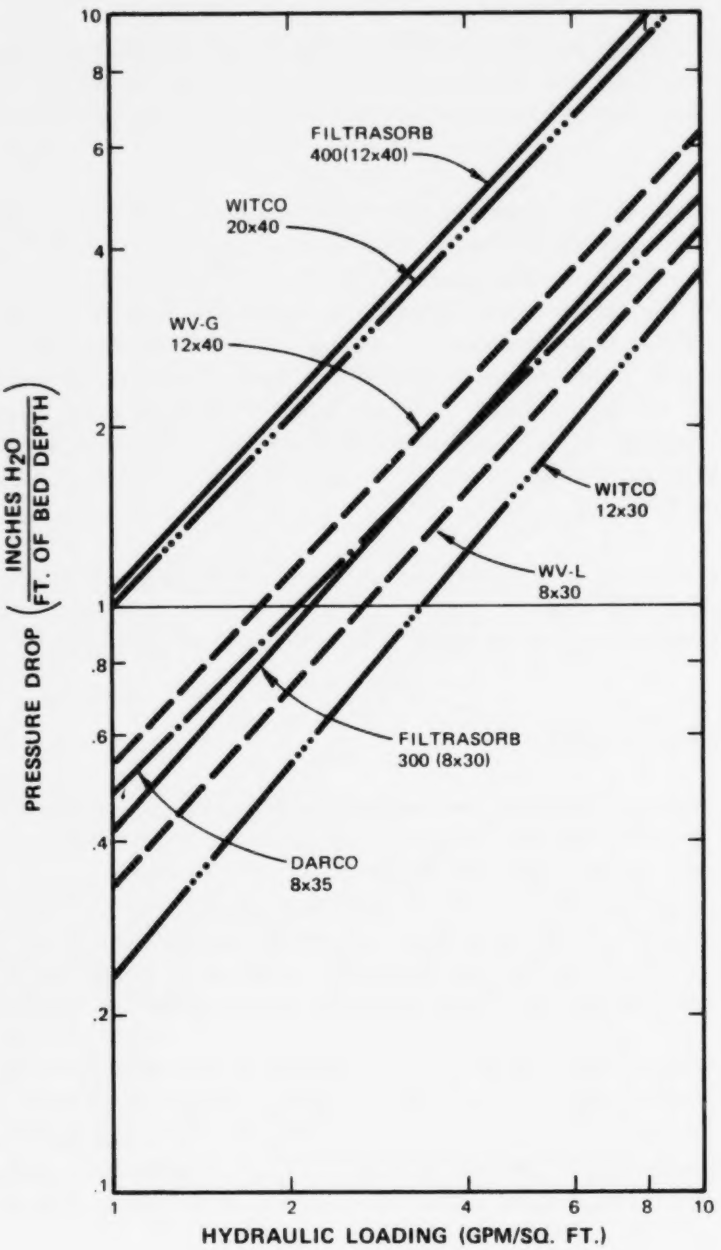


FIGURE 3–4

PRESSURE DROP VS. HYDRAULIC LOADING

gravity versus pressurized flow may also be influenced by the anticipated rate of headloss development. Very high hydraulic loadings are practical only in pressurized systems. Gravity flow in downflow beds is considered practical only at hydraulic loadings less than about 4 gpm/sq ft.

Upflow expanded beds should be considered when high headloss is expected. At low flow rates, the particles are undisturbed and the bed remains fixed. As the flow rate is increased, however, a point is reached where all particles no longer remain in contact with one another, and the carbon bed is expanded in depth. The flow rate required for initial expansion of the bed is accompanied by a sizable increase in headloss. As the flow rate is increased, there is further expansion of the bed. Flow rates required for further expansion of the bed are accompanied by lesser increases in headlosses. Figure 3-5 illustrates the sharp increase in ΔP for initial bed expansion and the lower rate of increase for further expansion. Figure 3-6 shows expansion of 8 x 30 and 12 x 40 mesh carbon beds at various flow rates.

It has been found that at about a 10 percent expansion of an upflow bed, suspended solids will pass through the bed. In Figure 3-6, a 10 percent expansion occurs at approximately 6 gpm/sq ft for 12 x 40 mesh carbon and about 10 gpm/sq ft for 8 x 30 mesh carbon.

3.4.7 Backwash Requirements

The purpose of backwashing is to reduce the resistance to flow caused by solids that have accumulated in the bed. The rate and frequency of backwash is dependent upon the hydraulic loading, the nature and concentration of the suspended solids in the wastewater, the carbon particle size, and the method of contacting (upflow, downflow). A contactor operating at a hydraulic loading of 7 gpm/sq ft may be backwashed daily to counteract excessive pressure drop. The same contactor operated at 3.5 gpm/sq ft, with the same suspended solids loading,may require backwashing only every 2-1/2 days.

Backwash frequency may be determined by any of several criteria: buildup of headloss, deterioration of effluent turbidity, or at regular predetermined intervals of time. It may be convenient for operational reasons to arbitrarily backwash beds at one-day intervals, for example, without regard for headloss or turbidity. The other criteria may only be of interest during periods of shock solids loading when backwash frequency exceeds once per day.

The removal of solids trapped in a packed upflow bed may require two steps: first, the bottom surface plugging may have to be relieved by temporarily operating the bed in a downflow mode, and second, the suspended solids entrapped in the middle of the bed may have to be flushed out by bed expansion.

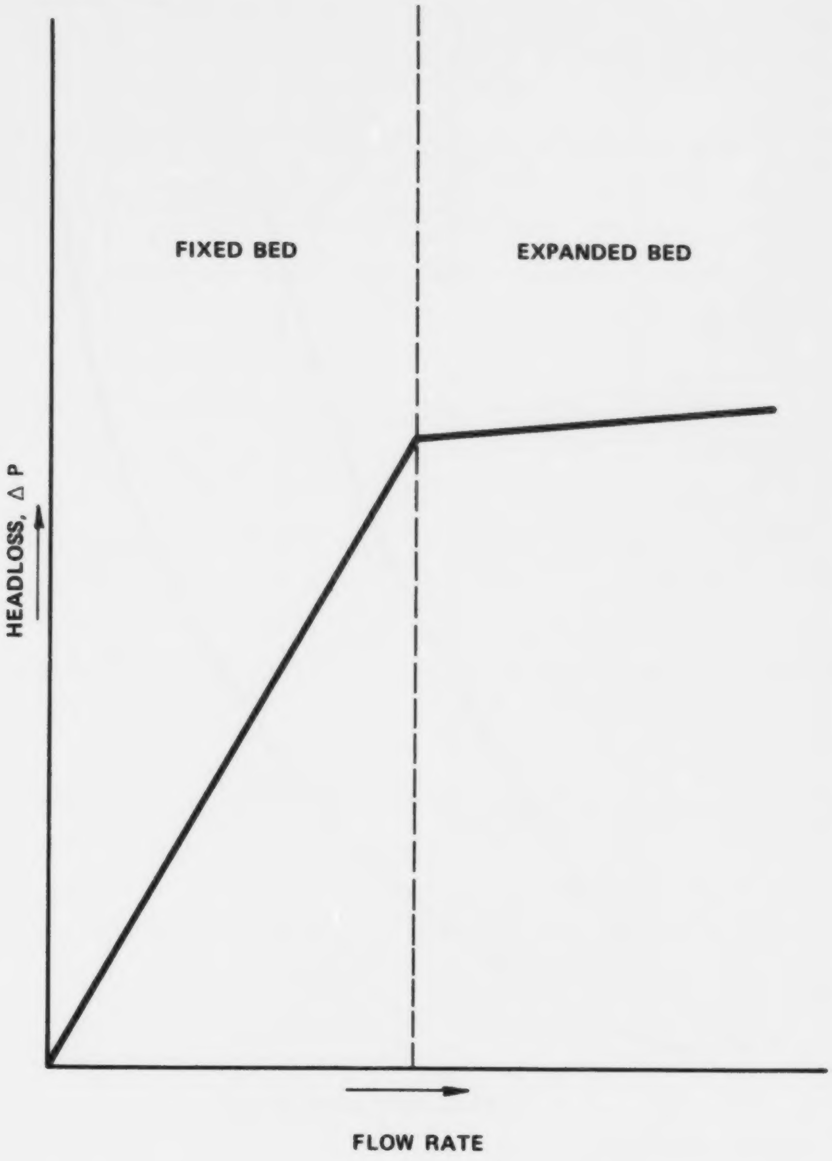
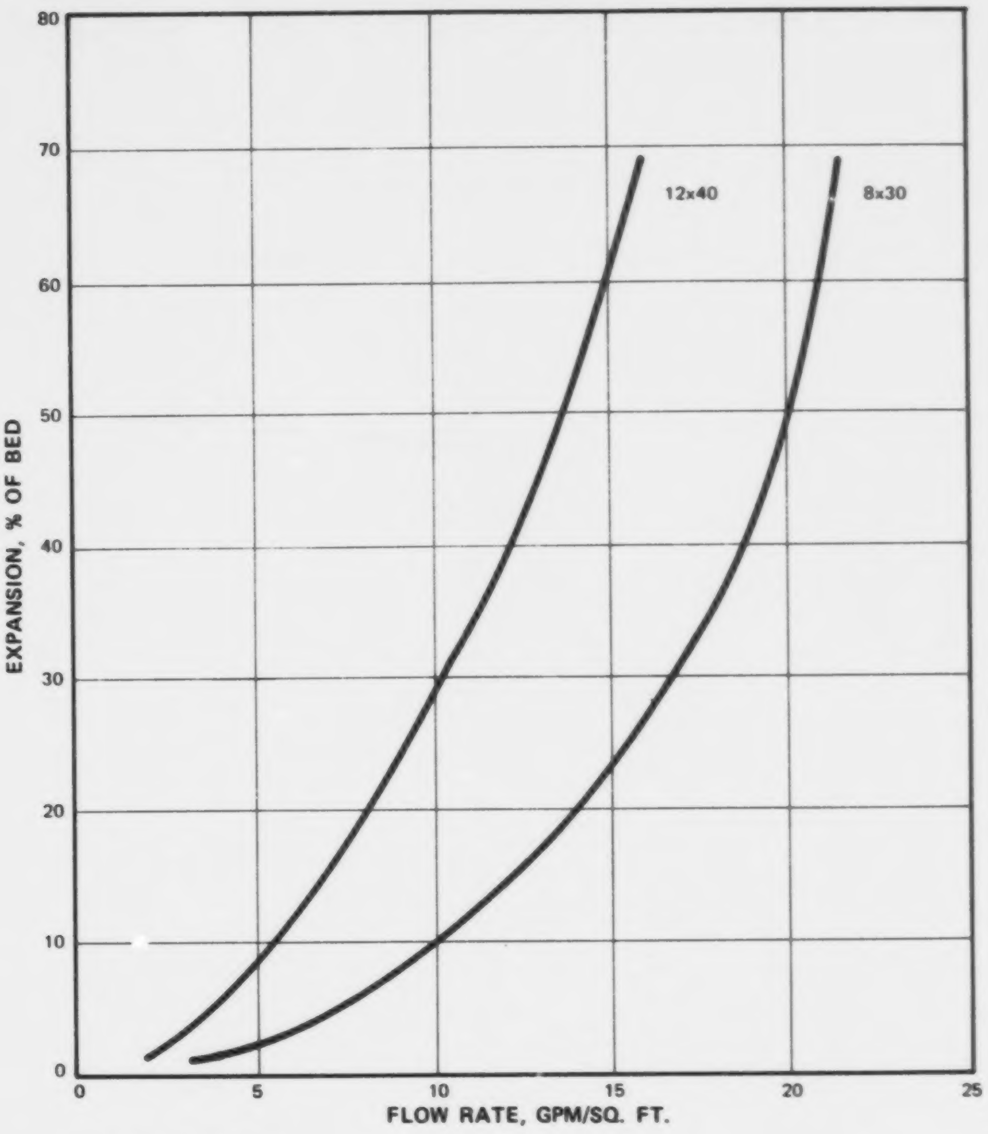


FIGURE 3–5

HEADLOSS ON BED EXPANSION



CARBON: 12x40, 8x30
LIQUID: WATER AT 22° C

FIGURE 3–6

EXPANSION OF CARBON BED AT VARIOUS FLOW RATES

Often backwashing of packed upflow carbon contactors, which are preceded by filtration, merely consists of increasing upflow from the normal rate of 5 to 6 gpm/sq ft (for 8 x 30 mesh carbon) to 10 to 12 gpm/sq ft for 10 to 15 minutes.

Backwashing a downflow contactor normally requires a bed expansion of 10-50 percent. It is recommended that provisions for backwash flow rates of 12-20 gpm/sq ft be made with the granular carbons of either 8 x 30 mesh or 12 x 40 mesh. Effective removal of the solids accumulated on the carbon surface in downflow contactors requires: (a) surface wash equipment utilizing rotating or stationary nozzles for directing high pressure streams of water at the surface of the bed, (b) an air wash, or (c) a combination air-water wash. A surface wash or air wash system is normally operated only during the first few minutes of a backwash of 10-15 minutes. When backwashing is supplemented by this scouring type of wash, the total amount of water to achieve a given degree of bed cleaning may be reduced. Also, surface wash or air wash overcomes bed plugging that may not be alleviated by normal backwash velocities. As a general rule, the total amount of backwash water required should not exceed 5 percent of the average plant flow.

Backwash water may be effectively disposed of by recirculating it into the primary sedimentation basin or elsewhere near the inlet of the wastewater treatment plant. A return flow equalization tank may be advisable in order to reduce shock hydraulic loads on the plant from waste washwater. This is particularly true for small plants.

Air scouring has been used successfully in test programs and appears to be suitable for large-scale use. It is being used at Colorado Springs [2] and it is an accepted technique in water filter operation.

Basically, the technique involves draining the water level to within about one foot of the top of the carbon bed followed by introducing air at a rate of about 3 to 10 CFM/sq ft to the bottom of the column at a velocity that will thoroughly agitate the entire carbon bed. For breaking biological slimes from the carbon particles, 5 minutes of air scour should be sufficient.

3.4.8 Air and Vacuum Release Requirements

Pressure carbon columns must be provided with an air and vacuum release valve, protected by a screen to avoid plugging by carbon particles. Air must be released when filling the column and the vacuum must be broken when draining a column to avoid structural damage to the vessel. A detail of a typical air-vacuum release valve installation is shown in Figure 3-7.

3.5 Biological Activity in Carbon Contactors

Under certain conditions, granular carbon beds provide favorable conditions for the production of hydrogen sulfide (H_2S) gas which has an unpleasant odor, and which may

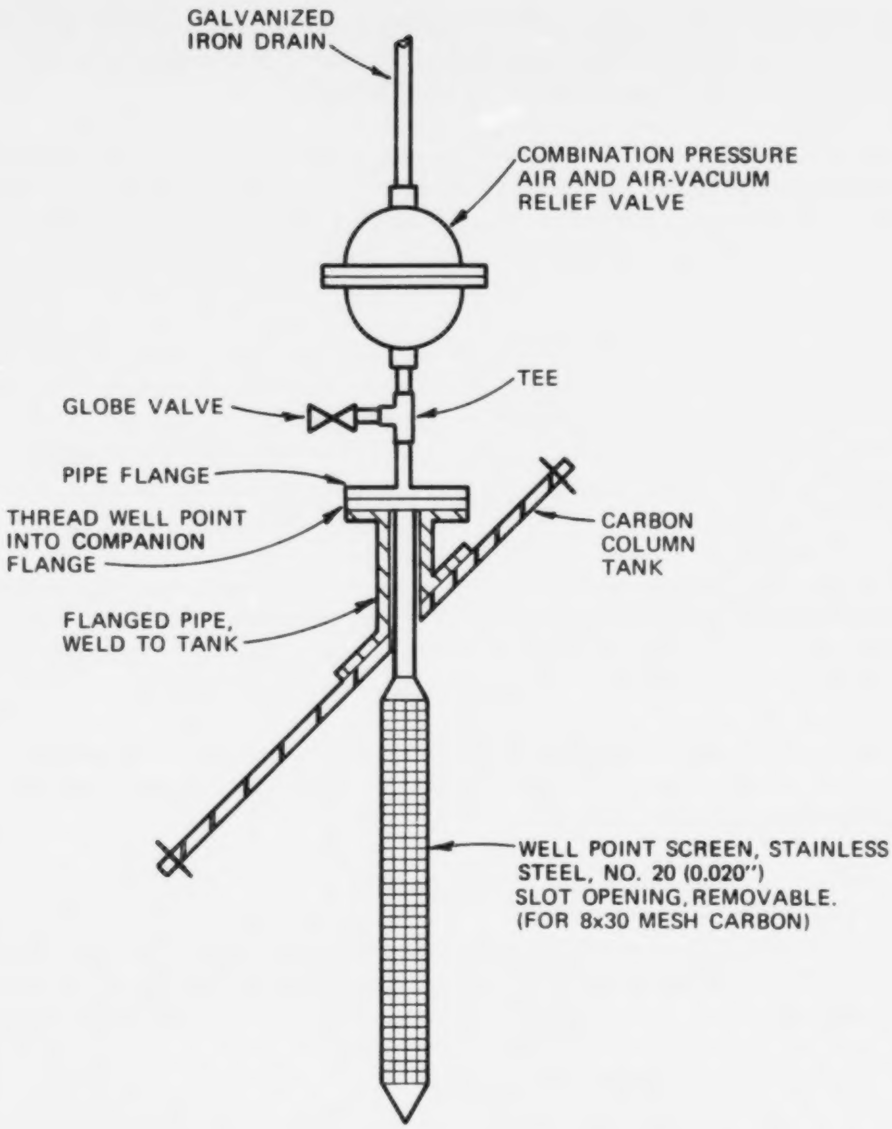

GALVANIZED
IRON DRAIN
COMBINATION PRESSURE
AIR AND AIR-VACUUM
RELIEF VALVE
TEE
GLOBE VALVE
PIPE FLANGE
THREAD WELL POINT
INTO COMPANION
FLANGE
CARBON
COLUMN
TANK
FLANGED PIPE,
WELD TO TANK
WELL POINT SCREEN, STAINLESS
STEEL, NO. 20 (0.020")
SLOT OPENING, REMOVABLE.
(FOR 8x30 MESH CARBON)

FIGURE 3–7

AIR-VACUUM RELEASE VALVE DETAIL

contribute to corrosion of metals and damage concrete. The hydrogen sulfide is produced by sulfate-reducing bacteria under anaerobic conditions. Conditions promoting or accelerating the production of hydrogen sulfide in carbon contactors include:

1. Low concentrations or absence of dissolved oxygen and nitrate in the carbon contactor influent.

2. High concentrations of BOD and sulfates.

3. Long detention times.

4. Low flow-through velocities.

It may be possible to prevent or correct problems of hydrogen sulfide generation by eliminating one or more of the conditions necessary to sustain growth of the sulfate-reducing bacteria. Most of the preventive measures must be provided in the design of the carbon contacting system, but there are also some corrective measures which can be taken in plant operation. The amount of actual plant operation experience in this regard is limited. In plant design, the following measures may be taken to provide flexibility for dealing with problems of hydrogen sulfide production:

1. Satisfy as much of the oxygen demand of the wastewater as possible by providing biological treatment prior to carbon treatment.

2. Provide biological treatment and efficient filtration to reduce the load of suspended and dissolved organics thus permitting the use of higher flow-through velocities and reduced detention times in the carbon columns.

3. In packed beds of carbon, provide facilities for application of chlorine to the influent. In addition, in upflow expanded beds it may be desirable to provide for introduction of air, oxygen, or sodium nitrate (as a source of oxygen). Because of the mass of cell growth produced, it may be less desirable to introduce air or oxygen ahead of packed beds because of potential physical plugging of the beds. These growths are flushed through expanded upflow beds, but may be removed in sections of the plant which follow such as filters or clarifiers.

Some remedial measures available in the operation of carbon facilities are:

1. Columns may be backwashed at more frequent intervals or backwashed more violently by use of air scour or surface wash.

2. Detention time may be reduced by taking some carbon contactor units off the line, provided that the reduced carbon contact time is still sufficient to obtain the desired removal of organics and that headlosses in the carbon columns remaining on the line do not become excessive.

3. Chlorination or oxygen addition may be initiated.

As an example of correction in actual plant scale operation in a tertiary process sequence, an incident at the South Tahoe plant is reviewed. The carbon facilities at this location are provided with all of the design features recommended above. In eight years (1965-1973) of carbon column operation, there has been only one occasion (in 1970) of about three days duration of hydrogen sulfide production. When the odor was detected in the carbon column effluent, it was observed that plant flow was less than half the design flow, and 7 of the 8 carbon columns were in service. This meant that the contact time was more than 40 minutes rather than the normal 17 minutes. Three of the columns were backwashed with water containing DO and taken off the line. The remaining four columns were similarly backwashed and operated at near the full design throughput rate, but with the addition of 2 to 3 mg/l of chlorine to the influent. After two days of operation on this basis, hydrogen sulfide odors were no longer detected in the carbon column effluent.

In operations at the PCT pilot research facility at Pomona, California [3], it was found that:

1. Measures which were used successfully at Tahoe to end H_2S production in carbon columns were not adequate when the influent consists of raw wastewater that has received only chemical clarification.

2. Continuous chlorination of the carbon column influent at dosages up to 50 mg/l reduced significantly, but did not stop H_2S production.

3. Intermittent backwash, surface wash, and oxygen addition reduced, but did not completely eliminate H_2S.

4. Intermittent backwash, surface wash, and continuous oxygen addition to DO = 4 mg/l reduced sulfide formation, but stimulated biological growth and headloss in the carbon bed.

5. The addition of air wash to normal backwash and surface wash was not effective against H_2S, and 7 inches of carbon was lost from the bed.

6. The continuous addition of sodium nitrate to the carbon column influent at the rate of 4 to 5 mg/l as NO_3 - N completely inhibited H_2S generation in the column.

At the Cleveland Westerly pilot plant [4], all efforts to eliminate sulfide odors in carbon columns following PCT were found to be impractical. However, the BOD of the carbon column influent at this plant ranged from 80 to 100 mg/l as opposed to around 40 mg/l at Pomona. The control methods used were: (1) daily backwashing at 10 gpm/sq ft plus surface wash at 2 gpm/sq ft for 28 minutes, (2) continuous addition of $NaNO_3$ to the influent, and (3) backwashing with water containing 27 mg/l of chlorine (from NaOCl). At dosages of 100 mg/l of $NaNO_3$ (expressed as NO_3^-) sulfide production was eliminated, but this high dosage was not considered economically practical.

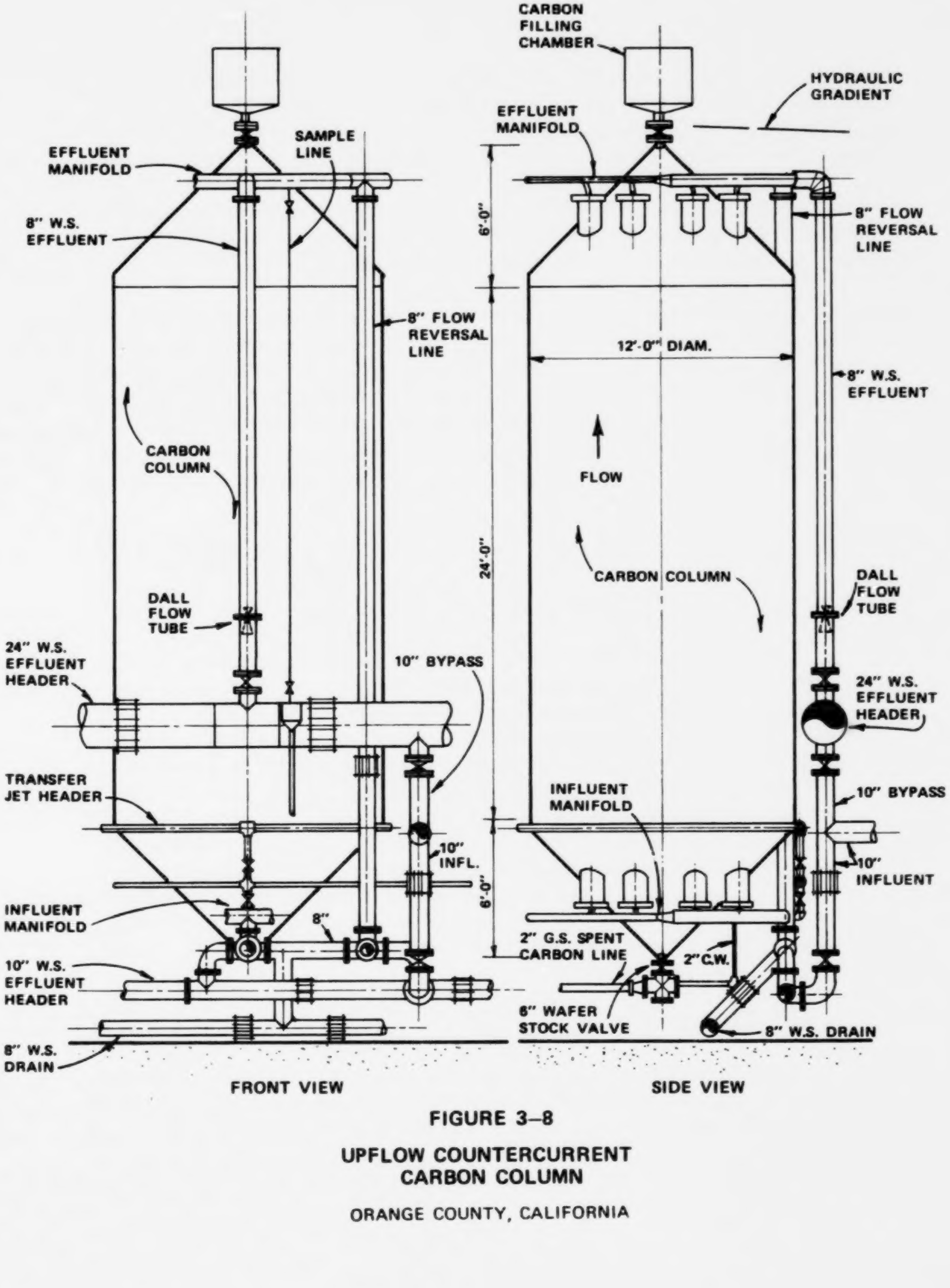
Sulfides in the carbon column effluent can be removed by precipitation with iron or by the addition of chlorine. However, at this time the most effective means of coping with the H_2S problem appears to be to maintain aerobic conditions in the carbon contactors rather than trying to remove H_2S after it is formed. If the BOD applied to the carbon is less than 5 mg/l, as is the case in most tertiary treatment schemes, the H_2S problem is easily controlled. For applied BOD values substantially higher than this, it appears that use of upflow, aerobic expanded contactors followed by sedimentation or filtration is preferable.

3.6 Design Examples

3.6.1 Upflow, Packed Bed, Pressurized

Figure 3-8 shows the upflow countercurrent packed bed carbon columns being installed (1973) at the Orange County, California Water District (OCWD) tertiary treatment plant. These are the last treatment units (except those for breakpoint chlorination) in a 15 mgd plant employing chemical clarification, nitrogen removal and multi-media filtration. Reclaimed water from this plant will be blended with desalted seawater for ground water recharge. Similar carbon columns are being designed for the 22.5 mgd Upper Occoquan Sewage Authority plant in Virginia. Similar type contactors have been in service for eight years at the 7.5 mgd South Tahoe, California plant (except that the Tahoe columns have 12 feet long straight sidewalls rather than 24 feet, and provide 17 minutes contact rather than 30 minutes as at OCWD and Occoquan). In each of these three plants, biologically treated wastewater is subjected to high lime clarification ($pH > 10.5$), ammonia removal, recarbonation, and mixed-media filtration prior to application to the carbon. Applied turbidities will range from 0.1 to 1.0 JTU.

At the OCWD plant, there are 17 carbon columns each 12 feet in diameter with a 24 feet long straight sidewall. At a plant flow of 15 mgd, 16 of these columns will provide 30 minutes nominal contact with the carbon. The 17th column is a spare, also to be used for carbon storage. Each of the columns contains 2,700 cubic feet of 8 x 30 mesh carbon and the hydraulic loading at design flow is 5.8 gpm/sq ft. Exterior views of these columns are shown in Figure 3-8; details of the inlet and outlet screens are shown in Figure 3-9; Figures 3-10 and 3-11 show the top screen system and the carbon filling chamber.


CARBON FILLING CHAMBER
HYDRAULIC GRADIENT
EFFLUENT MANIFOLD
SAMPLE LINE
EFFLUENT MANIFOLD
8" W.S. EFFLUENT
8" FLOW REVERSAL LINE
6'-0"
8" FLOW REVERSAL LINE
12'-0" DIAM.
8" W.S. EFFLUENT
CARBON COLUMN
FLOW
24'-0"
CARBON COLUMN
DALL FLOW TUBE
DALL FLOW TUBE
24" W.S. EFFLUENT HEADER
10" BYPASS
24" W.S. EFFLUENT HEADER
TRANSFER JET HEADER
INFLUENT MANIFOLD
10" BYPASS
10" INFL.
10" INFLUENT
6'-0"
INFLUENT MANIFOLD
8"
2" G.S. SPENT CARBON LINE
2" C.W.
10" W.S. EFFLUENT HEADER
6" WAFER STOCK VALVE
8" W.S. DRAIN
8" W.S. DRAIN

FRONT VIEW SIDE VIEW

FIGURE 3–8

UPFLOW COUNTERCURRENT CARBON COLUMN

ORANGE COUNTY, CALIFORNIA

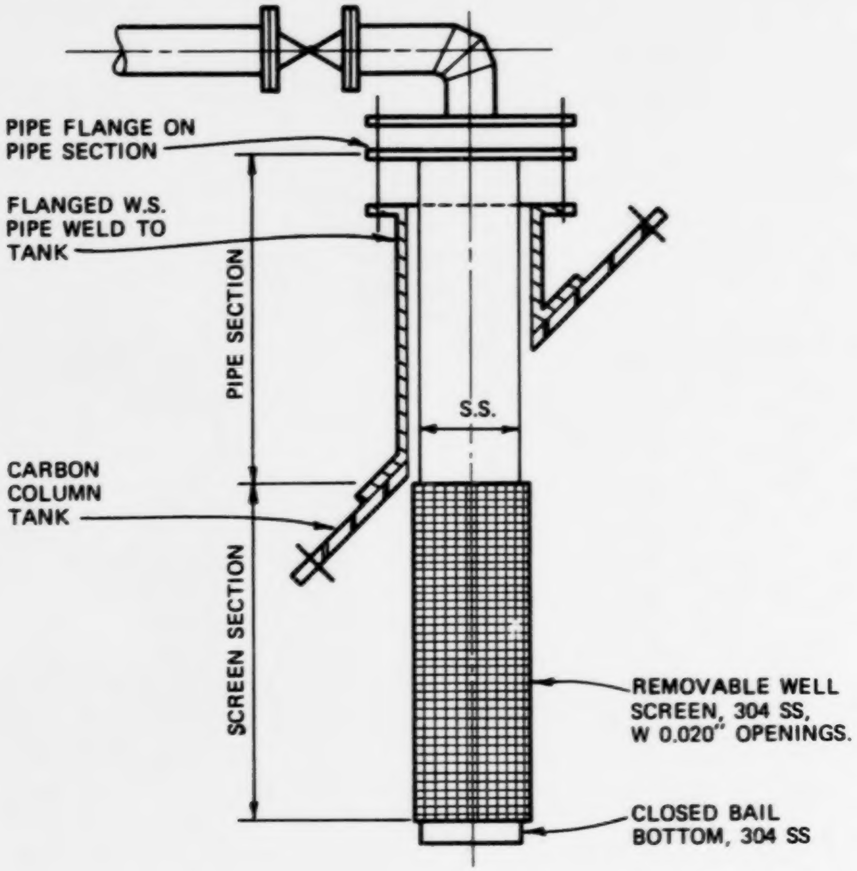

PIPE FLANGE ON
PIPE SECTION
FLANGED W.S.
PIPE WELD TO
TANK
PIPE SECTION
S.S.
CARBON
COLUMN
TANK
SCREEN SECTION
REMOVABLE WELL
SCREEN, 304 SS,
W 0.020" OPENINGS.
CLOSED BAIL
BOTTOM, 304 SS

FIGURE 3–9

TOP AND BOTTOM
UNDERDRAINS

ORANGE COUNTY, CALIFORNIA

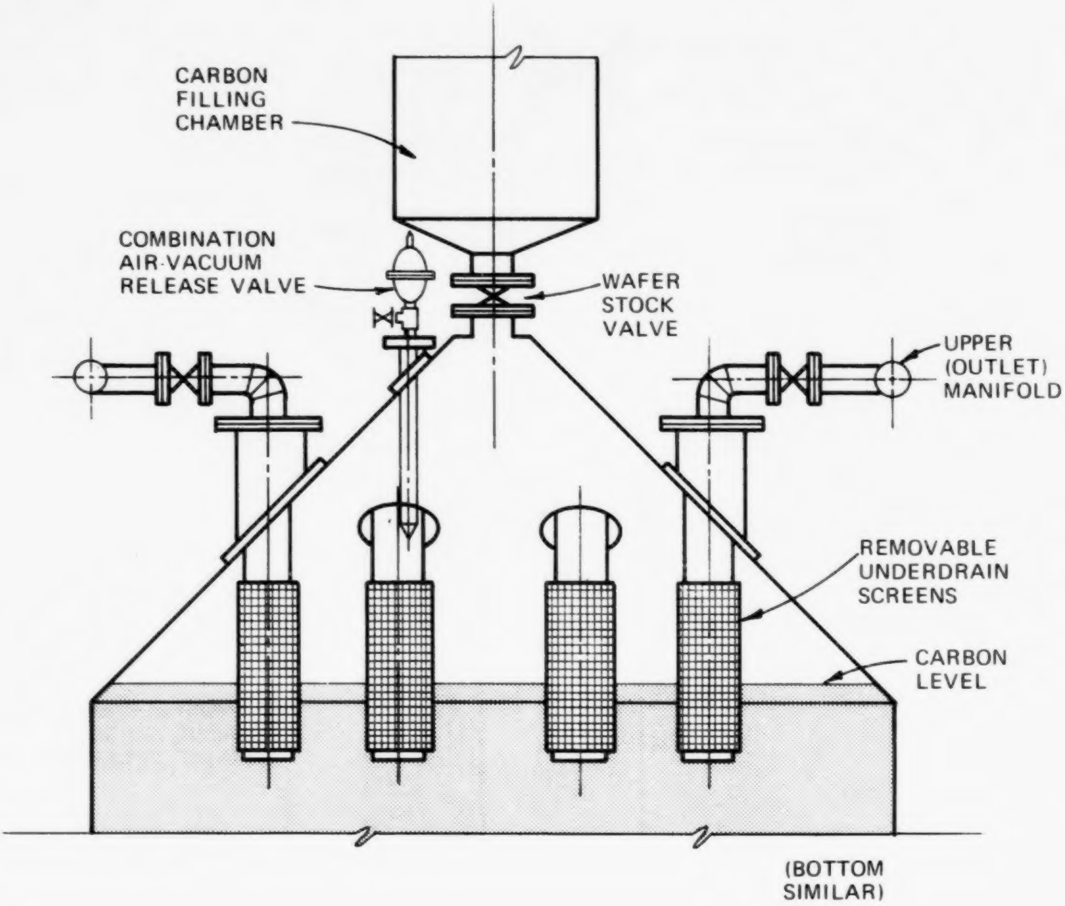

CARBON FILLING CHAMBER
COMBINATION AIR-VACUUM RELEASE VALVE
WAFER STOCK VALVE
UPPER (OUTLET) MANIFOLD
REMOVABLE UNDERDRAIN SCREENS
CARBON LEVEL
(BOTTOM SIMILAR)

FIGURE 3–10

SECTION THROUGH TOP UNDERDRAIN

ORANGE COUNTY, CALIFORNIA

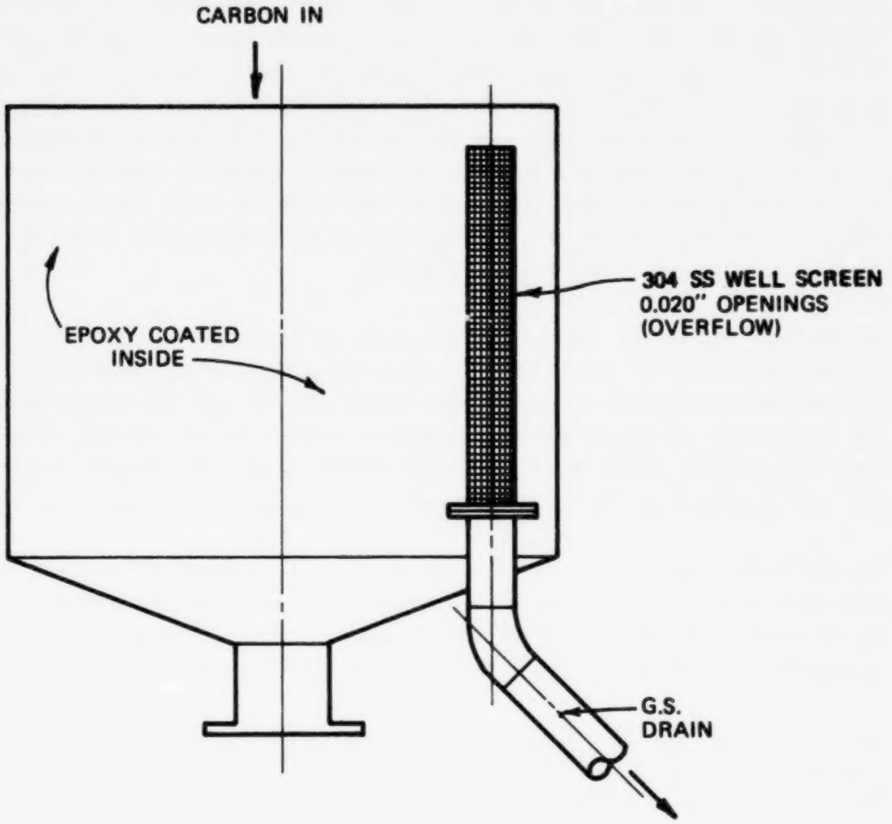

CARBON IN
EPOXY COATED INSIDE
304 SS WELL SCREEN 0.020" OPENINGS (OVERFLOW)
G.S. DRAIN

FIGURE 3–11

CARBON FILLING CHAMBER

ORANGE COUNTY, CALIFORNIA

Figure 3-12 shows the valve positions and flow pattern during the normal upflow adsorption or service cycle of the columns at the OCWD plant. Filtered water enters the bottom of the column through the screen manifold, flows upward through the carbon, and leaves through the upper screen manifold. The hydraulic gradient lies at a level between the top of the column and the carbon filling bucket. This makes it possible to add fresh carbon (regenerated and makeup) at the top and to withdraw spent carbon from the bottom while the column is in service. Therefore, carbon can be withdrawn slowly and more or less continuously and replaced with fresh carbon. If carbon withdrawal is intermittent, the usual practice is to withdraw and replace 5 to 10 percent of the total contents of one column at a time.

Figure 3-13 shows the upflow-to-waste cycle of operation which is used after a major transfer of carbon it if is necessary to clear the effluent of excessive carbon fines. Figure 3-14 shows the method of reversing flow downward through the column in order to clear the top screens of carbon particles lodged in screen openings. Reverse flow also removes any accumulated trapped particles in the bottom of the bed. Figure 3-15 merely shows the valve positions for bypassing a column for inspection, maintenance, or repair.

As shown on Figure 3-10, a void space of about 10 percent of the total carbon column volume is provided at the top of the columns. Occasionally, the flow to the column can be increased from the normal rate of 6.3 gpm/sq ft to a flow in excess of 10 gpm/sq ft to expand the carbon bed and to flush out particulate matter so as to reduce headloss.

By placing the elevation of the point of spent carbon discharge below the top of the carbon filling chamber on the column, it is possible to withdraw spent carbon by gravity flow from the column while it is in normal service. If more rapid transfer is desired, the wafer valve at the top of the column below the filling chamber may be closed and the entire column pressurized (with high pressure water supply) for carbon removal. Note that a pressure supply of dilution water is provided through a pipe cross at the bottom of the column. This allows water to be added as necessary to obtain the desired carbon slurry consistency for hydraulic transfer. The contactor is also equipped with a transfer jet header which furnishes pressure water through eight tangential nozzles at the top of the bottom cone. This water lubricates the cone surface and agitates the carbon to facilitate uniform withdrawal of carbon across the entire cross-sectional area of the column. This avoids dead spots and assists in obtaining maximum carbon efficiency.

3.6.2 Pulsed Bed, Pressurized

The contactor design already described for use as an upflow packed bed is suitable for operation as a pulsed bed. The pulsed bed differs from the upflow packed bed only in its method of operation which seeks to make the maximum possible use of the countercurrent principle by continuously withdrawing and replacing small quantities of carbon rather than in larger batches at intervals. Properly executed, this means that no

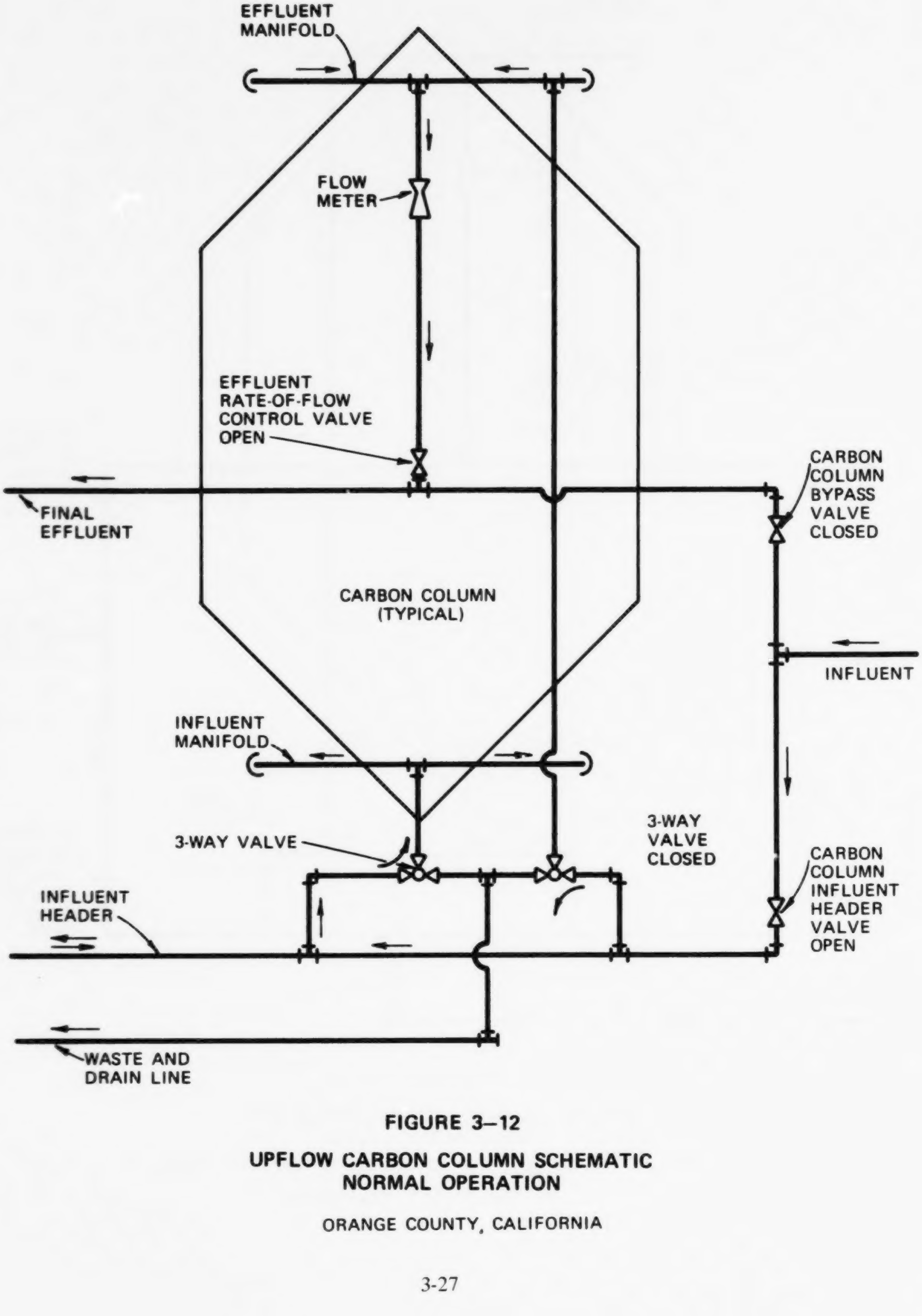

EFFLUENT MANIFOLD
FLOW METER
EFFLUENT RATE-OF-FLOW CONTROL VALVE OPEN
FINAL EFFLUENT
CARBON COLUMN BYPASS VALVE CLOSED
CARBON COLUMN (TYPICAL)
INFLUENT
INFLUENT MANIFOLD
3-WAY VALVE
3-WAY VALVE CLOSED
INFLUENT HEADER
CARBON COLUMN INFLUENT HEADER VALVE OPEN
WASTE AND DRAIN LINE

FIGURE 3–12

UPFLOW CARBON COLUMN SCHEMATIC
NORMAL OPERATION

ORANGE COUNTY, CALIFORNIA

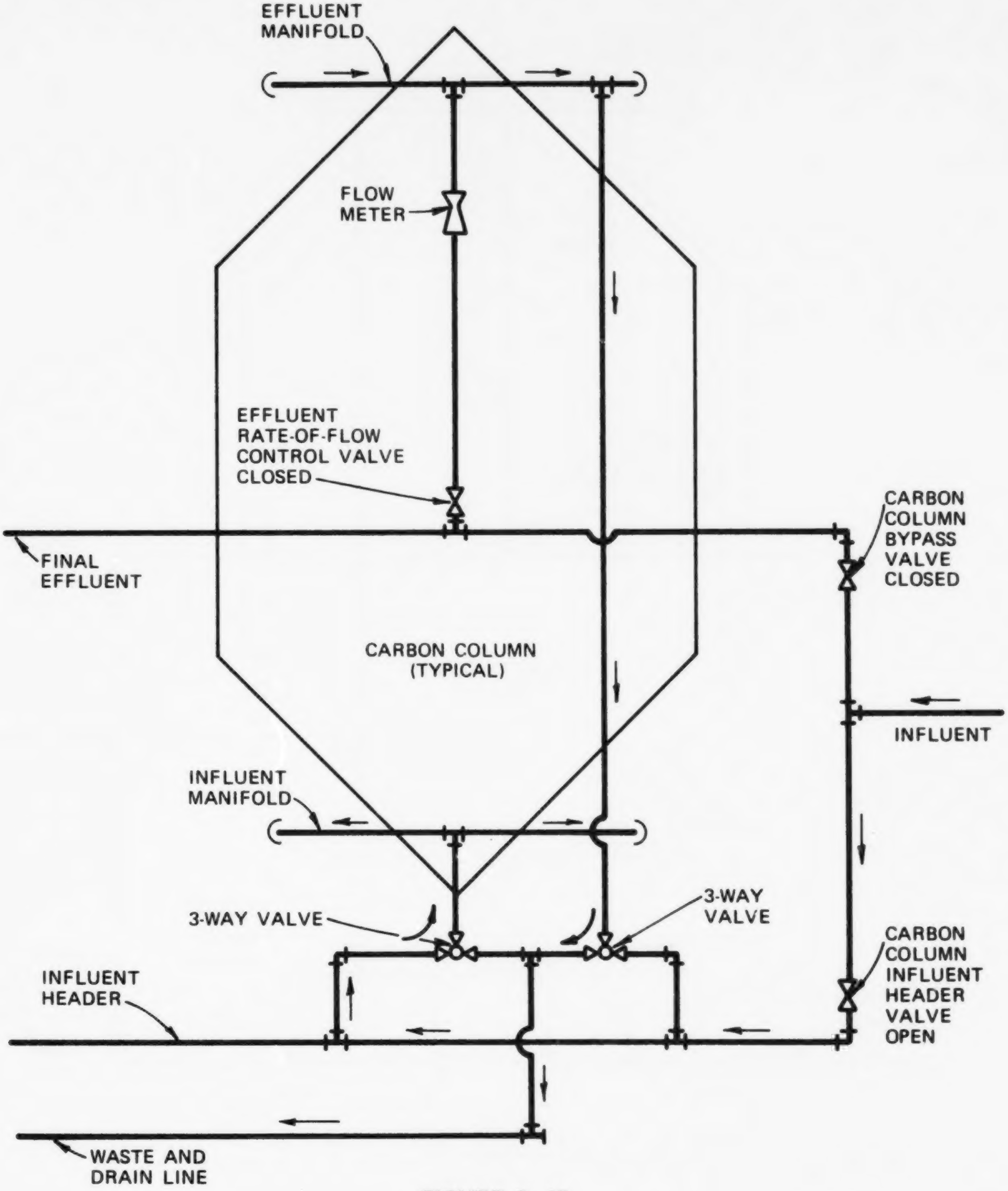

EFFLUENT MANIFOLD
FLOW METER
EFFLUENT RATE-OF-FLOW CONTROL VALVE CLOSED
CARBON COLUMN BYPASS VALVE CLOSED
FINAL EFFLUENT
CARBON COLUMN (TYPICAL)
INFLUENT
INFLUENT MANIFOLD
3-WAY VALVE
3-WAY VALVE
CARBON COLUMN INFLUENT HEADER VALVE OPEN
INFLUENT HEADER
WASTE AND DRAIN LINE

FIGURE 3–13

UPFLOW CARBON COLUMN SCHEMATIC
UPFLOW TO WASTE
(USED AFTER ADDING CARBON TO COLUMNS TO FLUSH OUT FINES)

ORANGE COUNTY, CALIFORNIA

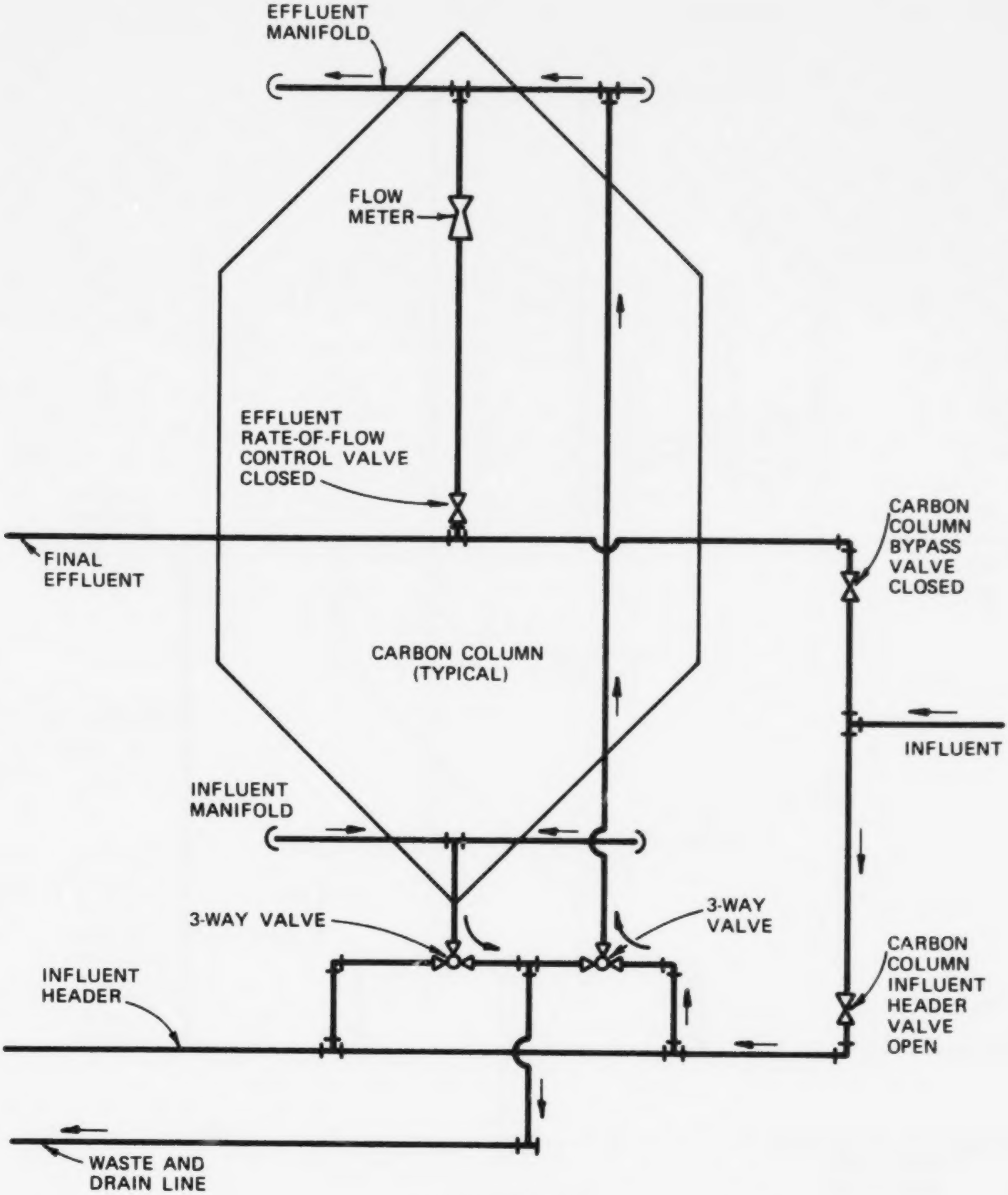

EFFLUENT MANIFOLD
FLOW METER
EFFLUENT RATE-OF-FLOW CONTROL VALVE CLOSED
CARBON COLUMN BYPASS VALVE CLOSED
FINAL EFFLUENT
CARBON COLUMN (TYPICAL)
INFLUENT
INFLUENT MANIFOLD
3-WAY VALVE
3-WAY VALVE
CARBON COLUMN INFLUENT HEADER VALVE OPEN
INFLUENT HEADER
WASTE AND DRAIN LINE

FIGURE 3–14

UPFLOW CARBON COLUMN SCHEMATIC – REVERSE FLOW

(USED TO FLUSH TOP SCREENS)

ORANGE COUNTY, CALIFORNIA

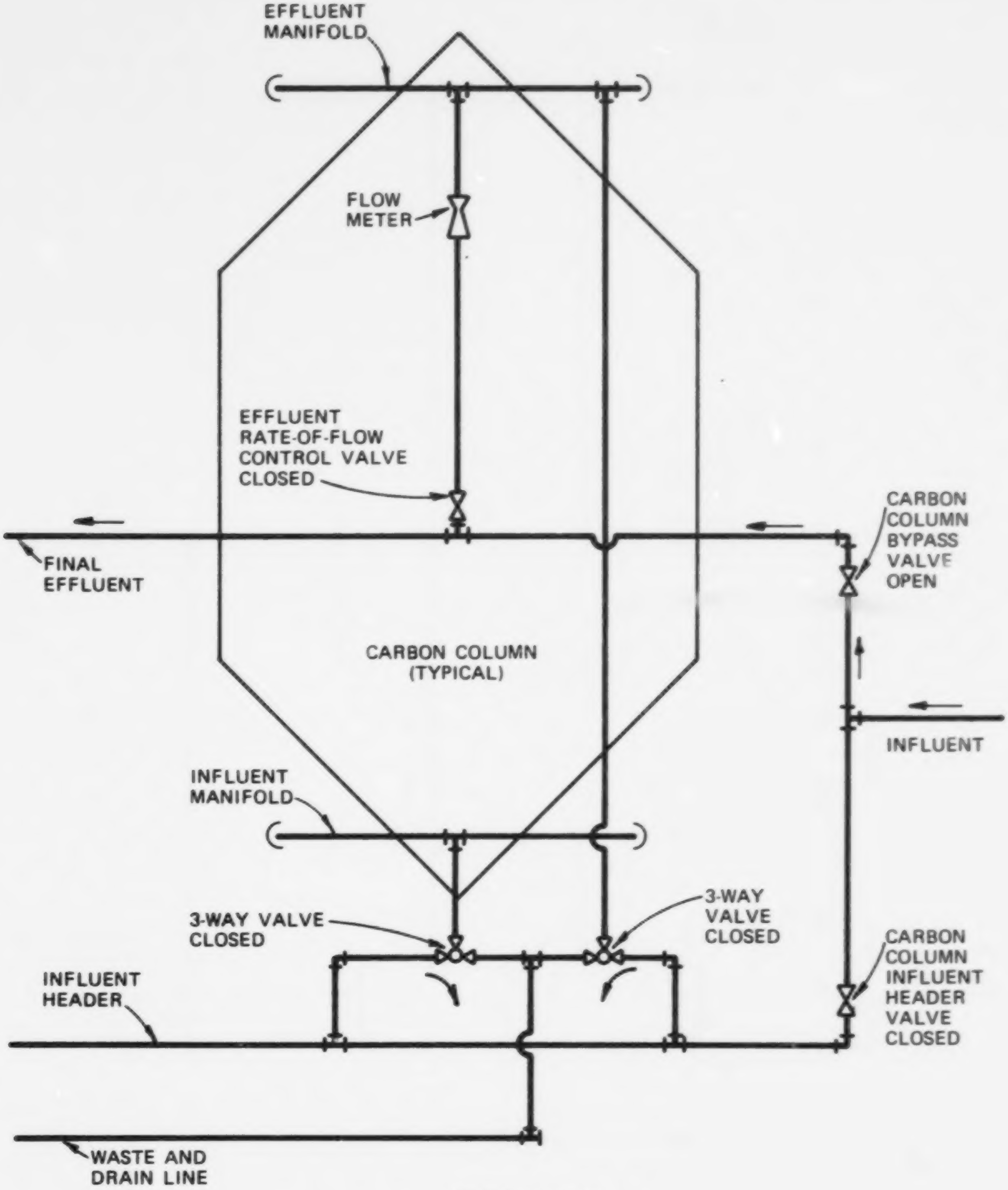

EFFLUENT MANIFOLD
FLOW METER
EFFLUENT RATE-OF-FLOW CONTROL VALVE CLOSED
CARBON COLUMN BYPASS VALVE OPEN
FINAL EFFLUENT
CARBON COLUMN (TYPICAL)
INFLUENT
INFLUENT MANIFOLD
3-WAY VALVE CLOSED
3-WAY VALVE CLOSED
CARBON COLUMN INFLUENT HEADER VALVE CLOSED
INFLUENT HEADER
WASTE AND DRAIN LINE

FIGURE 3–15

UPFLOW CARBON COLUMN SCHEMATIC BY-PASSING CARBON COLUMN

ORANGE COUNTY, CALIFORNIA

particle of carbon is withdrawn from use until it is completely exhausted in its capability to adsorb organics even from the most concentrated wastewater which it contacts at the bottom flow inlet (exhausted carbon outlet).

In contrast, any batch method of withdrawal involves removal of a mixture of partially exhausted and completely exhausted carbon, compromising the countercurrent principle. The larger the batch withdrawn, the greater the compromise and loss of carbon efficiency. The single downflow reactor is the least efficient of all in this respect of withdrawing carbon which is not fully saturated. With pulsed bed operation, the carbon filling chamber would be kept full, or nearly so, in order that fresh carbon would automatically keep the column full while exhausted carbon is being removed from the bottom outlet.

3.6.3 Upflow Packed Bed, Open

The maximum diameter for factory fabricated steel tanks for carbon column vessels is about 12 feet (to permit highway transport). In large wastewater treatment plants a 12 feet limit on diameter requires an excessive number of units to handle the total flow. This means that steel vessels on-site fabricated or poured in place reinforced concrete vessels should be used for large carbon contactors.

The cost of constructing large pressurized vessels on site is often so high that open vessels are used. For upflow packed columns this introduces at least two new factors. First of all, the freeboard from the surface of the carbon to the top of sidewall should allow for 10 percent expansion of the carbon plus freeboard. Also, the method of introducing carbon is changed from a single point to a multiple point arrangement. Even with several points of carbon introduction, it is necessary to operate large diameter open contactors at upflow backwash rates after carbon addition in order to distribute the fresh carbon across the entire top surface of the bed. This approaches, but does not equal, the uniformity of distribution obtained from a central point at the top of the 45 degree conical top used in smaller diameter beds.

Figure 3-16 is a sketch of a potential design for a 30-feet diameter by 26-feet carbon depth reinforced concrete column. These columns would provide a 30 minute contact time at a hydraulic loading of 6.5 gpm/sq ft. Not shown in the drawing are the beams necessary to support the inlet and outlet screens.

3.6.4 Upflow Expanded Bed, Open

This type of carbon contactor is proposed for a 13 mgd (peak flow = 28 mgd) PCT plant at Vallejo, California. The treatment process will consist of high lime (pH=11) treatment of raw wastewater, single stage recarbonation, carbon adsorption, and dual-media filtration. Figure 3-17 illustrates the open upflow expanded bed carbon contactor to be

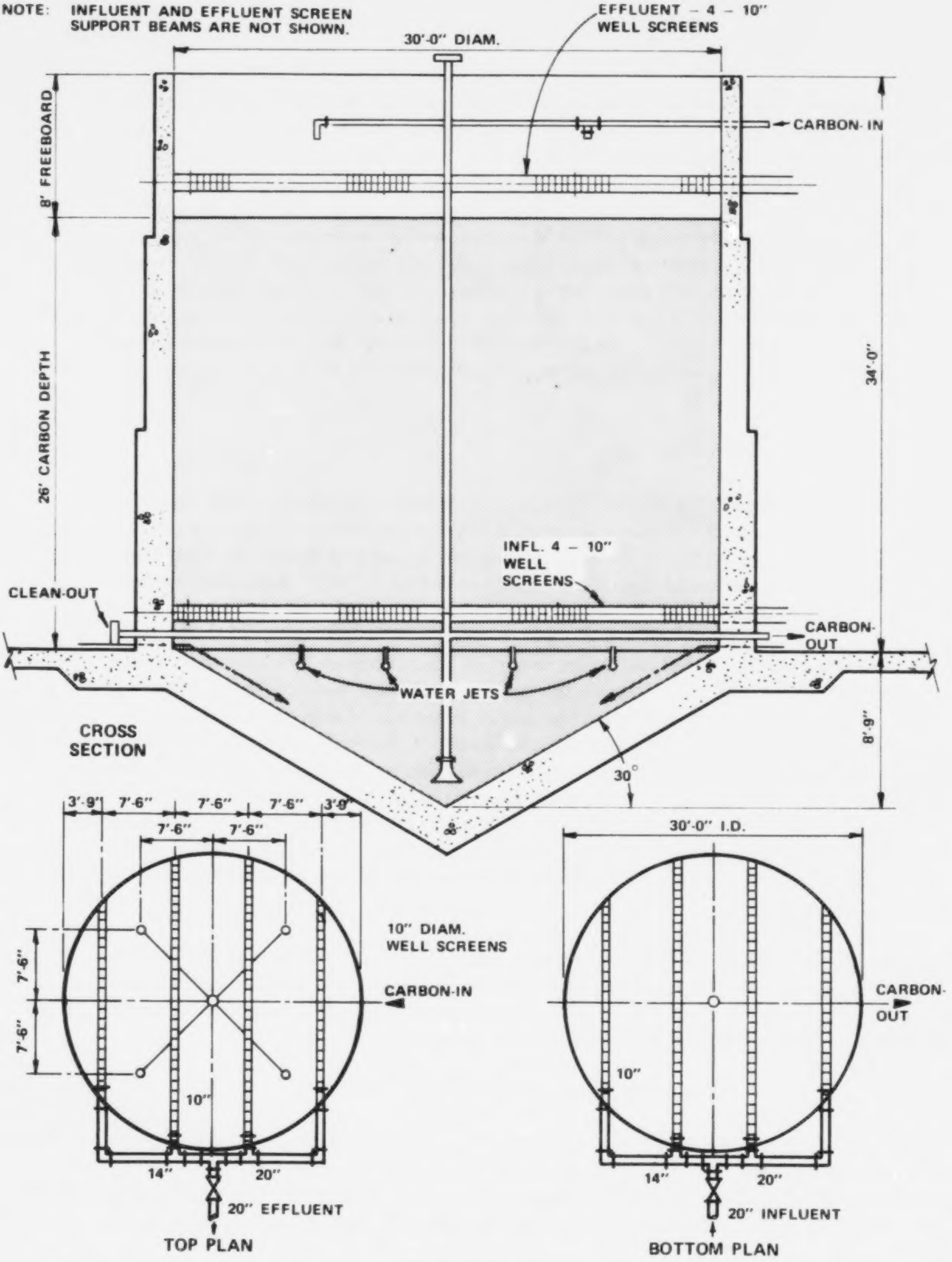

NOTE: INFLUENT AND EFFLUENT SCREEN SUPPORT BEAMS ARE NOT SHOWN.
EFFLUENT – 4 – 10" WELL SCREENS
30'-0" DIAM.
CARBON-IN
8' FREEBOARD
26' CARBON DEPTH
34'-0"
INFL. 4 – 10" WELL SCREENS
CLEAN-OUT
CARBON-OUT
WATER JETS
CROSS SECTION
8'-9"
30°
3'-9"
7'-6"
7'-6"
7'-6"
3'-9"
7'-6"
7'-6"
30'-0" I.D.
10" DIAM. WELL SCREENS
7'-6"
7'-6"
CARBON-IN
CARBON-OUT
10"
10"
14"
20"
14"
20"
20" EFFLUENT
20" INFLUENT
TOP PLAN
BOTTOM PLAN

FIGURE 3–16
UPFLOW OPEN PACKED BED CONTACTOR

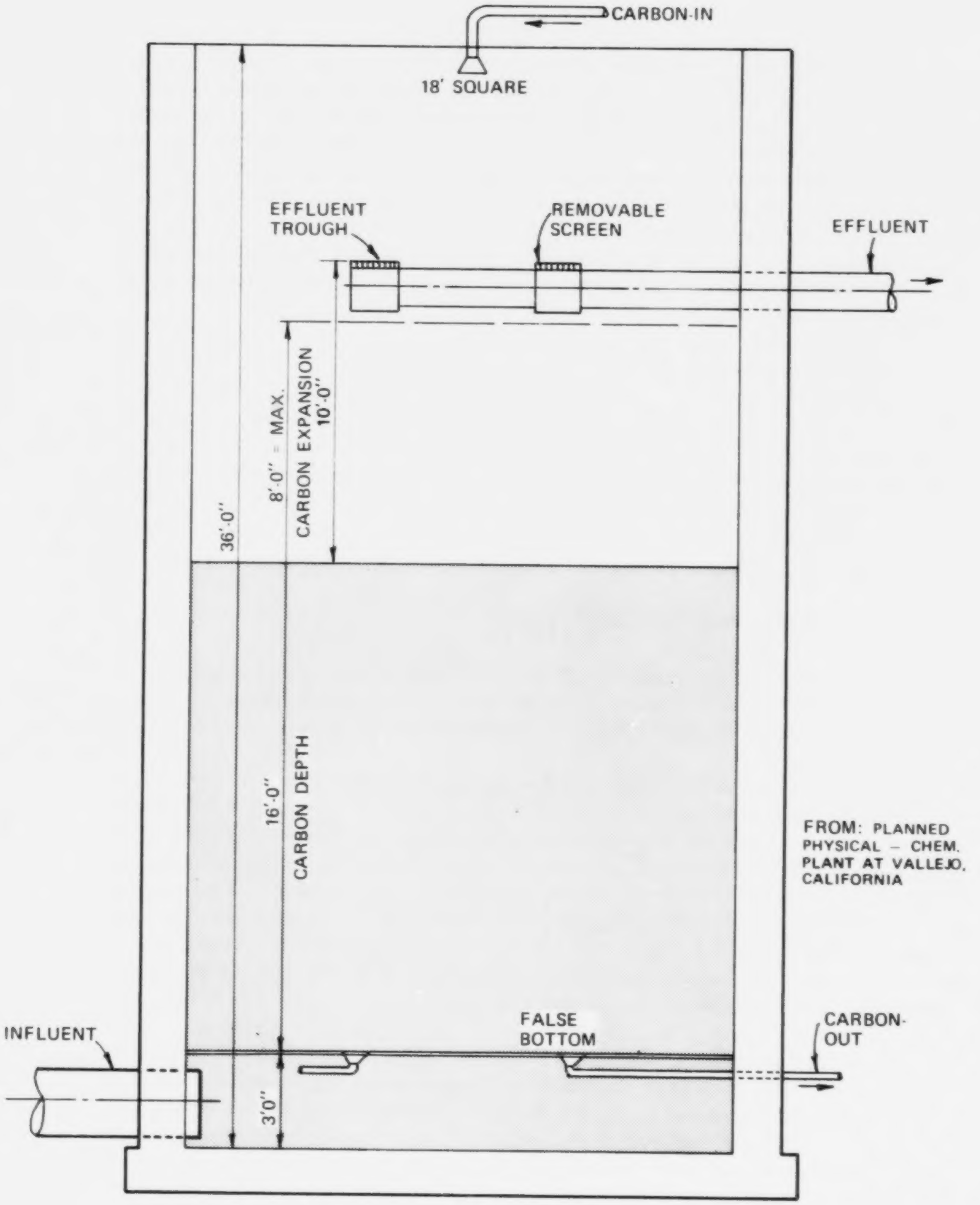

CARBON-IN
18' SQUARE
EFFLUENT TROUGH
REMOVABLE SCREEN
EFFLUENT
36'-0"
8'-0" = MAX.
CARBON EXPANSION 10'-0"
16'-0"
CARBON DEPTH
FROM: PLANNED PHYSICAL – CHEM. PLANT AT VALLEJO, CALIFORNIA
INFLUENT
FALSE BOTTOM
CARBON-OUT
3'0"

FIGURE 3–17

UPFLOW OPEN EXPANDED BED CONTACTOR

installed at Vallejo. There will be six contactors, each 18 feet square in plan by 36 feet deep. The beds will operate at an average hydraulic loading of 4.6 gpm/sq ft with a maximum rate of 10 gpm/sq ft. They will be equipped with air scour and hydraulic backwash at 15 gpm/sq ft. The 12 x 40 mesh carbon bed will be 16 feet deep and contact time varies from an average of 26 minutes to a minimum of 12 minutes. During normal operation, the carbon bed will be expanded by 10 percent and during backwash by 50 percent. The total headloss through the carbon is expected to be 4 to 5 feet. The beds will have a false bottom fitted with filter underdrain nozzles. Each bed will contain about 160,000 lbs of carbon for a total of 800,000 lbs. An additional 160,000 lbs of carbon will be held in reserve.

3.6.5 Upflow Expanded Bed, Pressurized

With carbon beds smaller than those schematically illustrated for Vallejo, it may be advantageous to use closed, pressurized, factory fabricated steel tanks. Some freeboard reduction might be made below that required for open top vessels, but space should be provided for 50 percent expansion. In operation of expanded carbon beds, there is some advantage to visual observation and control particularly in regulation of bed expansion under variable flow rates.

3.6.6 Downflow Packed Bed, Pressurized

Figure 3-18 illustrates the contactor of this type used in the original pilot plant at Pomona, California. It is equipped with surface wash and a double perforated metal plate false bottom which distributes washwater across the bottom of the bed.

This perforated plate, or any other flat bottom support system, must be designed to distribute the backwash water at the maximum anticipated rate and to withstand the associated uplift force. The maximum backwash velocity at Pomona, 12 gpm/sq ft, although adequate for expanding 16 x 40 mesh carbon, is not sufficient to provide 50 percent expansion of 8 x 30 mesh carbon. Even if backwash pumps were sized to force an upward flow of 20 gpm/sq ft through the carbon beds, the excessive pressure drop across the plates might force them to warp or to be dislodged. Special consideration is required to assure that these types of bottom support systems can hydraulically handle maximum flows in both directions and remain in place.

Removal of the major part of the carbon from the carbon bed is facilitated by keeping the bed flooded during withdrawal operations. The removal of the last stump or heel of carbon in the farthest corner of the bed from the withdrawal port may be difficult. A supplementary backwash (upflow) on the order of 3 to 6 gpm/sq ft, or nozzles in the side of the column just above the underdrain system, will aid in flushing this last quantity of carbon from the beds.

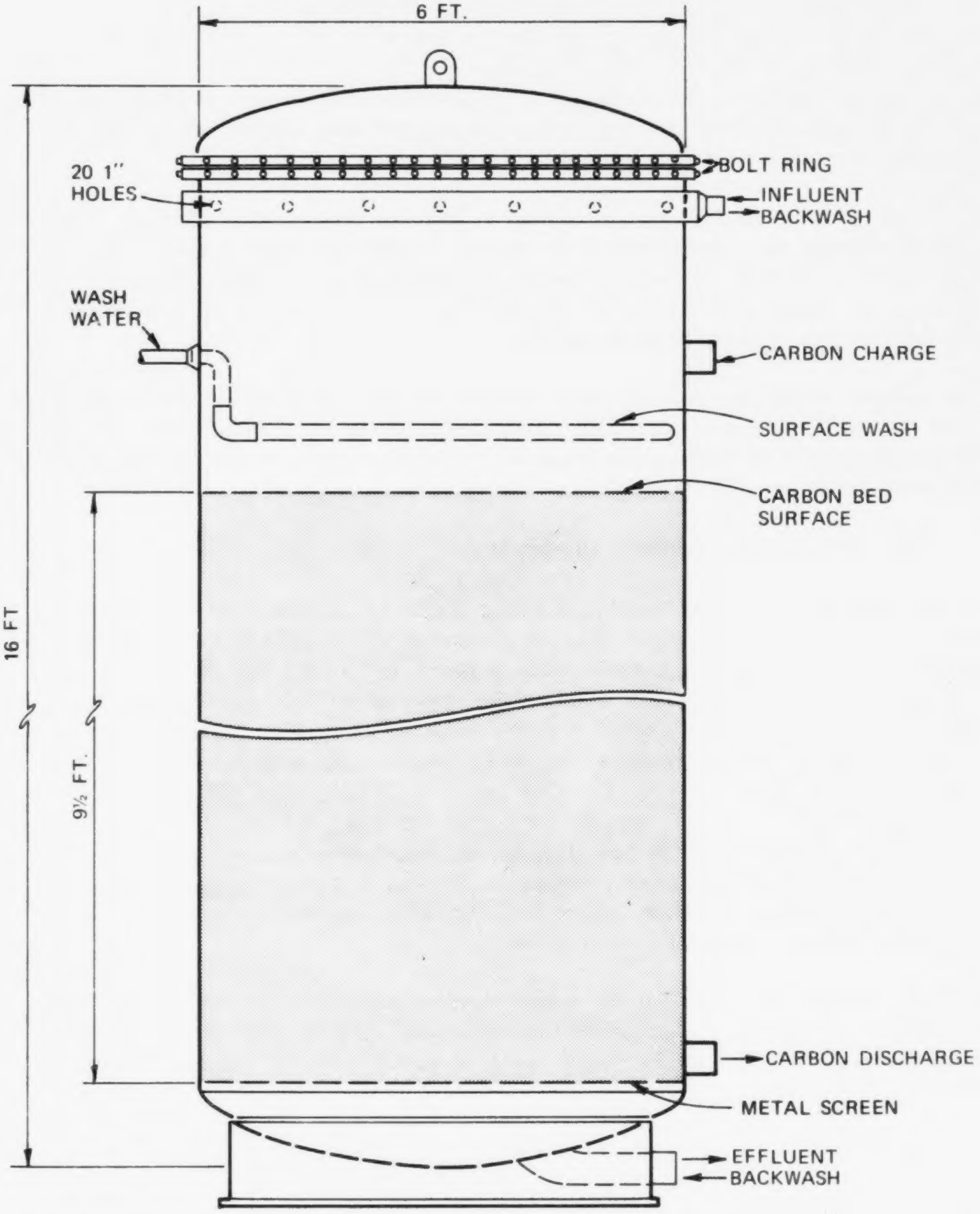

6 FT.
BOLT RING
20 1" HOLES
INFLUENT
BACKWASH
WASH WATER
CARBON CHARGE
SURFACE WASH
CARBON BED SURFACE
16 FT
9½ FT.
CARBON DISCHARGE
METAL SCREEN
EFFLUENT
BACKWASH

FIGURE 3–18

PRESSURIZED DOWNFLOW CONTACTOR
POMONA, CALIFORNIA

The Colorado Springs contactor (Figure 3-19) and the Rocky River contactor (Figure 3-20) both offer a flat bottom support for the carbon. Funnel shaped ports through the support are provided for carbon removal.

The actual bottom support system utilized is different for the two contactors. The Colorado Springs contactor (Figure 3-19) employs a perforated stainless steel plate into which filter underdrain nozzles are inserted for backwash control and distribution. In contrast, the Rocky River contactor (Figure 3-20) employs a porous tile filter bottom covered with several inches of graded gravel.

Flat bottoms commonly used in downflow beds have been used successfully for many years in water treatment plant filter design. They can be structurally sound and can provide adequate distribution of backwash flow, although there have been both structural and backwash system plant scale failures.

3.6.7 Downflow Packed Beds, Gravity, Open

Gravity downflow contactors may be designed similar to concrete rapid sand filters. A typical design is shown in Figure 3-21. The requirements to be satisfied in downflow carbon contacting are an adequate sidewall depth to provide for 50 percent bed expansion during backwash and a means for drawing off the spent carbon to be regenerated. Carbon can be removed from the contactor through a trough on top of the underdrain system or the installation of funnels similar to those employed at Colorado Springs or Rocky River.

A granular bed is an excellent flow distribution device not subject to flow channeling unless the hydraulic design for entering and leaving flow is poor or unless foreign solids are not regularly and completely washed from the bed so as not to accumulate and form mud balls. Surface wash or air scour is essential.

Gravity downflow contactors can be designed using existing sand filter technology, with the additional requirement for carbon withdrawal and addition noted above. The EPA Process Design Manual for Suspended Solids Removal may be consulted regarding filtration technology.

3.7 Carbon Inventory

While the size of carbon inventory required varies with the type of carbon contacting system used, this is a relatively minor item to be considered in selection of the contactors to be incorporated in the plant design.

With the use of upflow countercurrent beds operated in parallel, it is possible to operate without any storage of carbon within the plant. Needs for makeup carbon at the time of regeneration can be accurately anticipated both as to time when needed and quantity

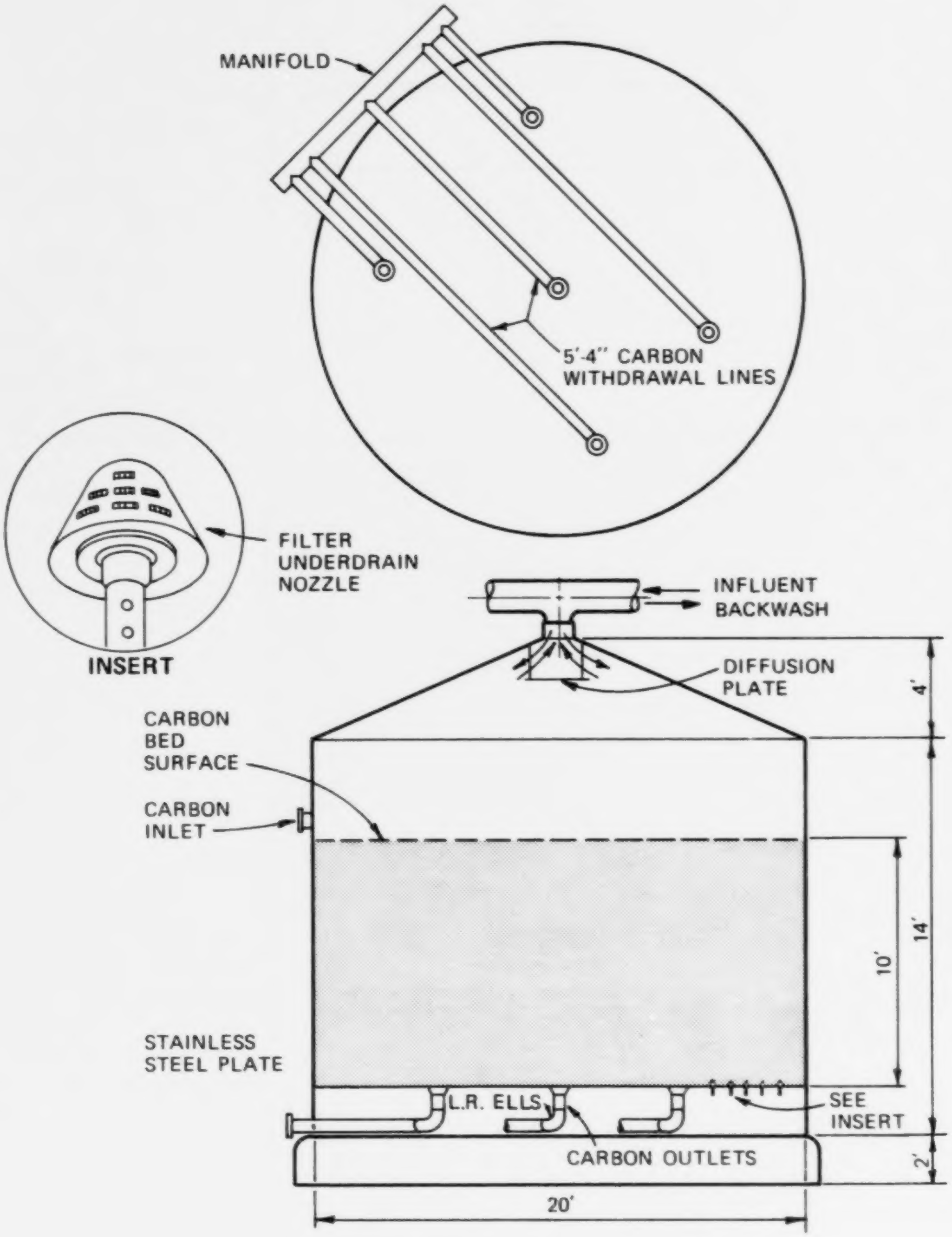

MANIFOLD
5'-4" CARBON WITHDRAWAL LINES
FILTER UNDERDRAIN NOZZLE
INSERT
INFLUENT
BACKWASH
DIFFUSION PLATE
CARBON BED SURFACE
CARBON INLET
STAINLESS STEEL PLATE
L.R. ELLS
SEE INSERT
CARBON OUTLETS
4'
14'
10'
2'
20'

FIGURE 3–19

PRESSURIZED DOWNFLOW CONTACTOR COLORADO SPRINGS, COLORADO

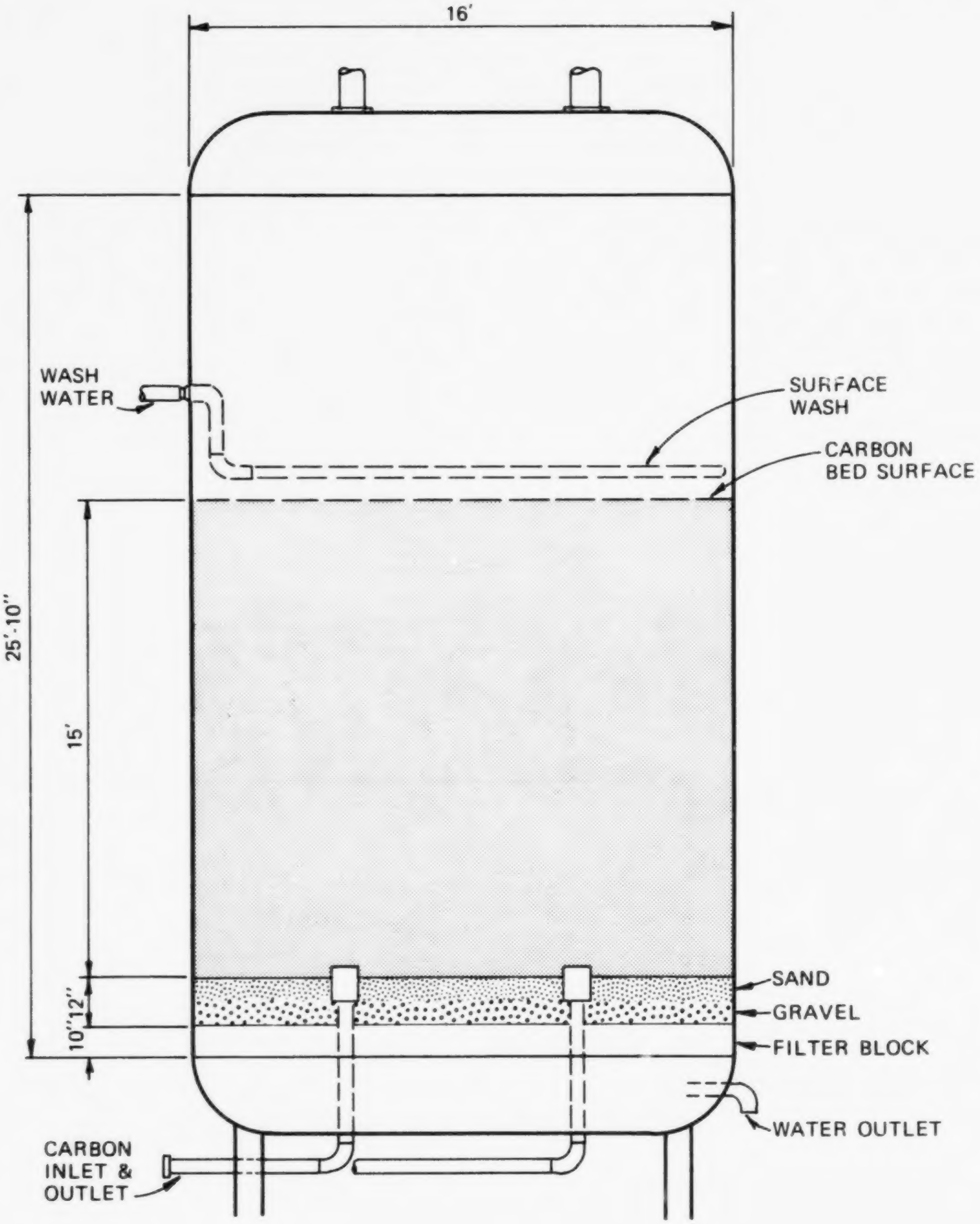

16'
WASH WATER
SURFACE WASH
CARBON BED SURFACE
25'-10"
15'
12"
10"
SAND
GRAVEL
FILTER BLOCK
WATER OUTLET
CARBON INLET & OUTLET

FIGURE 3–20

PRESSURIZED DOWNFLOW CONTACTOR
ROCKY RIVER, OHIO

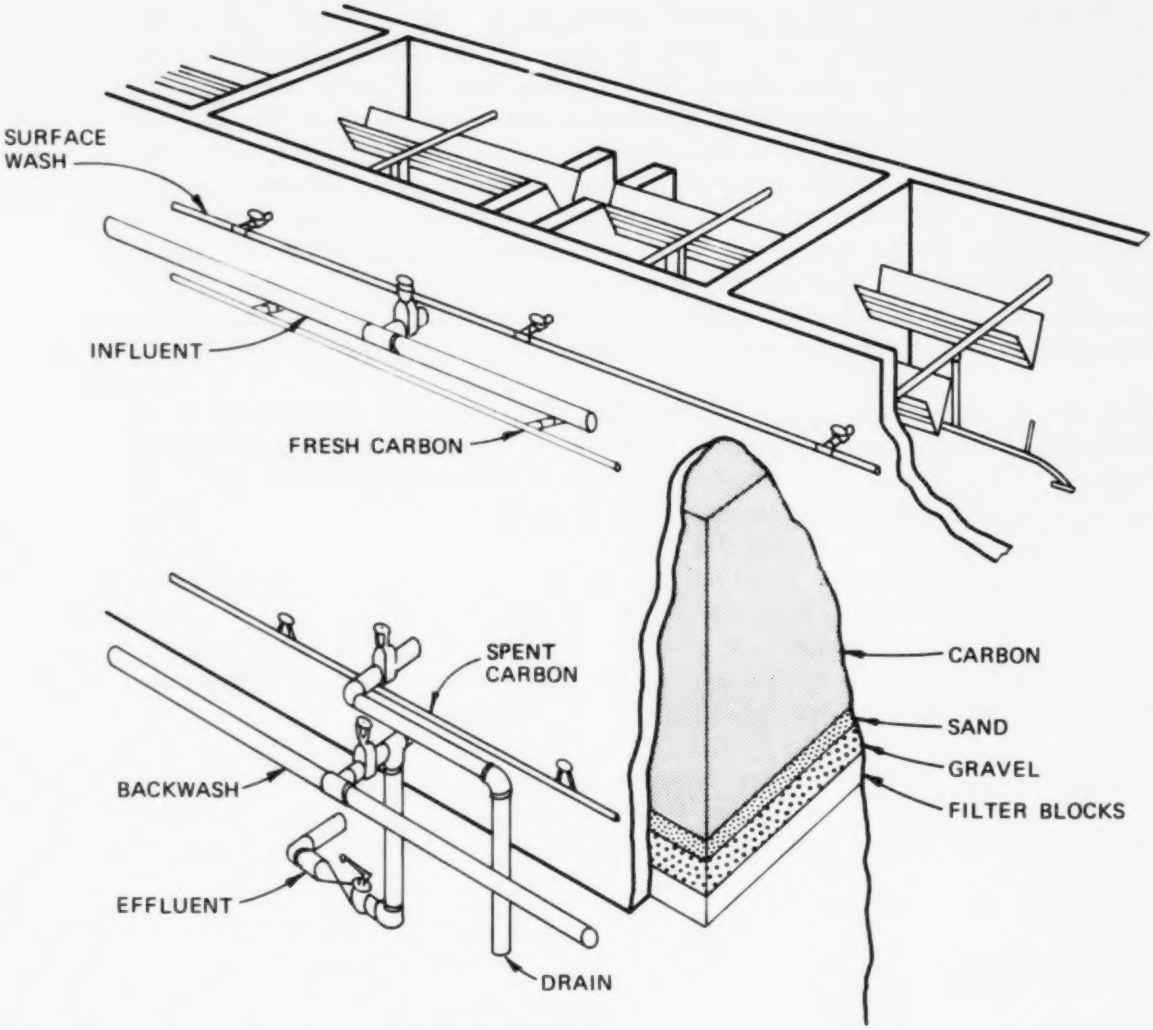

SURFACE WASH
INFLUENT
FRESH CARBON
SPENT CARBON
CARBON
SAND
GRAVEL
FILTER BLOCKS
BACKWASH
EFFLUENT
DRAIN

FIGURE 3–21

TYPICAL DOWNFLOW GRAVITY CONTACTOR

required, and the makeup carbon can be delivered at the proper time for direct addition to the contactors when space is available. Alternately, a carbon inventory equal to the makeup for one regeneration cycle (about 8 percent of the carbon to be regenerated) could be stored in the plant. Figure 3-22 illustrates how exhausted carbon can be withdrawn and makeup carbon can be added to an upflow column while the column is on stream and in service. In plants large enough to require several upflow columns to be operated in parallel, it may be desirable to provide one extra carbon column which can serve both as a redundant column and as a storage vessel for inventory carbon. The capital cost for a column is more than for an equal amount of storage in a tank equipped only for that purpose. However, the benefits of the dual use of the extra carbon contactor-storage vessel more than offset the additional cost, and the dual purpose unit is a good design feature which has been incorporated in several plants with upflow columns.

With the use of downflow columns, when carbon regeneration is required, the entire contents of a single downflow unit or the first of two downflow units in series must be withdrawn. This requires that one of the contacting units be taken out of service. A carbon inventory equal to the contents of one contactor must be maintained for filling the column which has been evacuated of carbon to be regenerated. With downflow contactors, it is good practice to provide two storage vessels each with a capacity for the contents of one contactor, one for exhausted carbon and one for makeup carbon. This may eliminate the need for the spare contactor if provision is made for rapid transfer of carbon in and out of the contactor from the two storage bins so as to limit the downtime for the out-of-service contactors to an acceptable period.

In any event, the costs for carbon inventory with the use of downflow contactors is greater than for upflow contactors. However, the cost difference is not large and may not have any great effect on the choice between upflow and downflow contactors.

3.8 Carbon Transport

3.8.1 General

The primary use of air or pneumatic transport of carbon is in bulk-handling of makeup carbon. Once carbon is introduced into the adsorption-regeneration system, it is usually transported hydraulically in slurry form.

When spent carbon is to be removed from a contactor, the bed is normally fluidized to allow the carbon to flow out of the contactor. Fluidizing of the bed assists in uniform withdrawal of the spent carbon and prevents "rat-holing". Spent carbon is moved hydraulically from the contactors to storage or dewatering facilities.

Handling characteristics have been experimentally studied by using water slurries of Pittsburgh type CAL 12 x 40 mesh granular carbon in a 2-inch pipeline. The data indicated that a maximum of 3 lbs of carbon per gallon of water could be transported

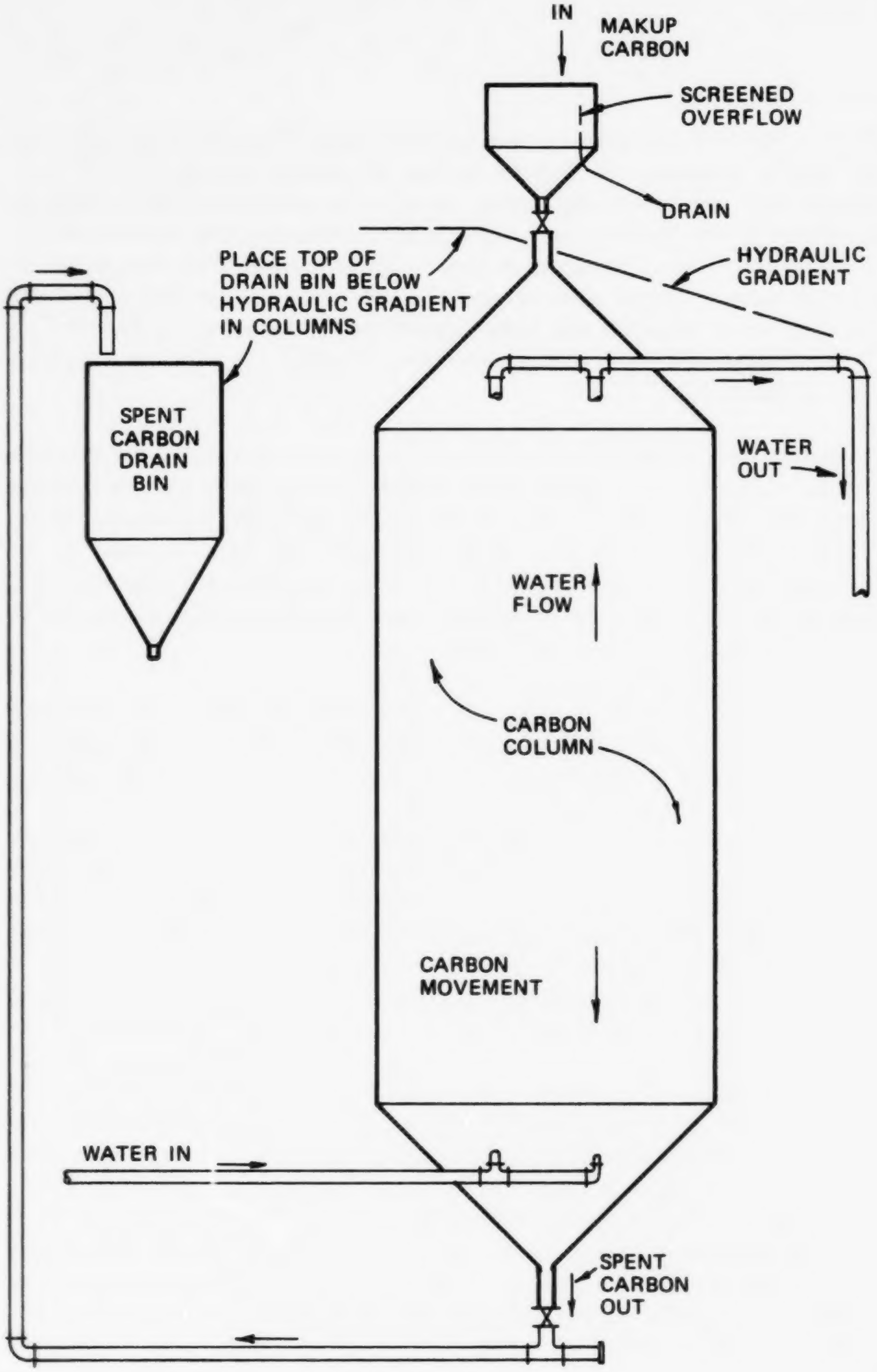

IN
MAKUP CARBON
SCREENED OVERFLOW
DRAIN
PLACE TOP OF DRAIN BIN BELOW HYDRAULIC GRADIENT IN COLUMNS
HYDRAULIC GRADIENT
SPENT CARBON DRAIN BIN
WATER OUT
WATER FLOW
CARBON COLUMN
CARBON MOVEMENT
WATER IN
SPENT CARBON OUT

FIGURE 3–22

CARBON TRANSFER WITH UPFLOW COLUMN IN SERVICE hydraulically, but that it is better to use one gallon of water for moving each pound of carbon. The velocity necessary to prevent settling of carbon is a function of pipe diameter, granule size, and liquid and particle density. The minimum linear velocity to prevent carbon settling was found to be 3.0 fps. It is recommended that a linear velocity between 3.5 to 5.0 fps be used. Velocities of over 10 fps are objectionable due to carbon abrasion and pipe erosion. Carbon delivery rates are a function of pipe diameter, slurry concentration, and linear velocity. Data from Calgon's studies are shown in Figures 3-23 and 3-24. Pressure drop data for various slurry concentrations and velocities in 2-inch pipe are shown in Figure 3-25.

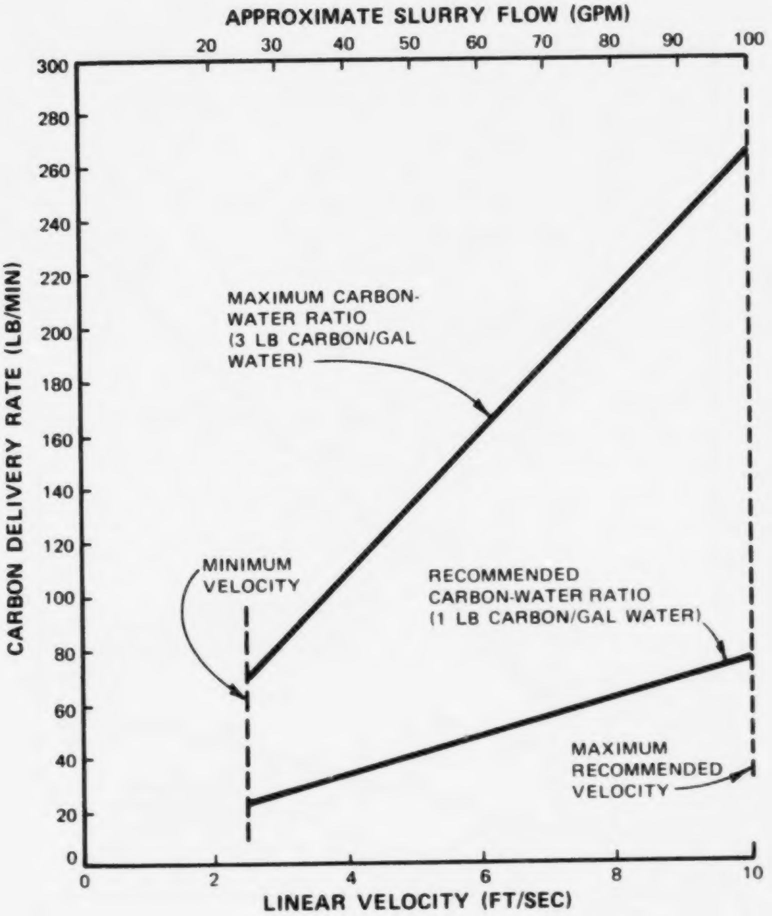
Pilot plant tests indicate that after an initial higher rate, the rate of attrition for activated carbon in moving water slurries is approximately constant for any given velocity reaching an approximate value of 0.12 percent fines generated per exhaustion-regeneration cycle. This deterioration of the carbon with cyclic operation has been reported to be independent of the velocity of the slurry (within the range recommended previously–3.5 to 5 fps). Loss of carbon by attrition in hydraulic handling apparently is not related to the type of pump (diaphragm or centrifugal) used.

Carbon slurries can be transported by using water or air pressure (blowcase), centrifugal pumps, eductors, or diaphragm pumps. The choice of motive power is a combination of owner preference, turndown capabilities, economics, and differential head requirements.

The blowcase uses air or water pressure applied in a specially designed pressure vessel to move the carbon slurry (see Figure 3-26). Carbon and water are slurried in a feed tank located above the pressure vessel. The slurry falls into the pressure vessel and the valve is closed. Air or water pressure is applied and moves the slurry out through the discharge pipe. This method has found considerable success in commercial installations. If water is used as the transporting medium, a suitable lining for mild steel or stainless steel should be used to eliminate corrosion (see section 3.12).

Centrifugal pumps of either the open or closed impeller type are suitable if minimum clearance for granule passage is maintained. Speed of the pump should be not more than 800-900 rpm to minimize degradation of the granules. A rubber or ceramic lined impeller is recommended for resistance to abrasion. Throttling of the discharge or suction should be avoided. Water jet eductors have been used successfully in specialized situations where the other type mechanisms are not practical or available. They are easy to operate and require little maintenance. Eductors have the disadvantage of being basically a single flow rate device with little turndown capability so that they must be designed for the maximum carbon flow and excess water is used at lesser carbon transfer rates.

For lower ranges of slurry concentrations any of the above mentioned pumps can be used. However, at higher slurry concentrations, diaphragm slurry pumps or blow tanks are preferred. For the pumping of a 25 percent granular carbon slurry, centrifugal pumps

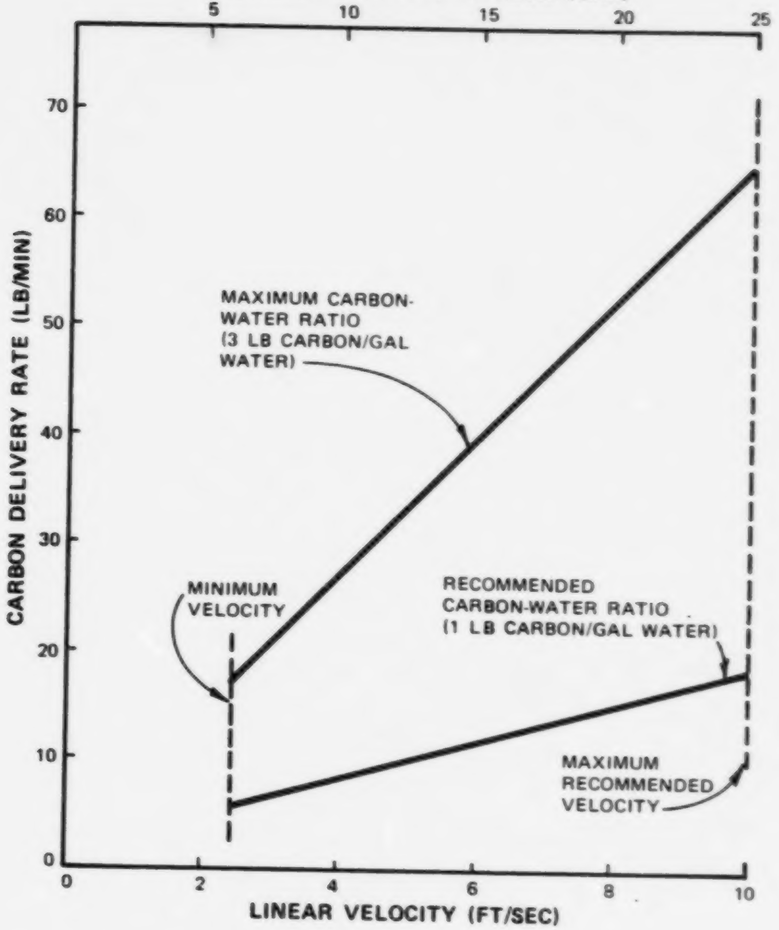


SOURCE: PITTSBURGH ACTIVATED
CARBON COMPANY

FIGURE 3–23

CARBON DELIVERY RATE

(2 INCH PIPE)

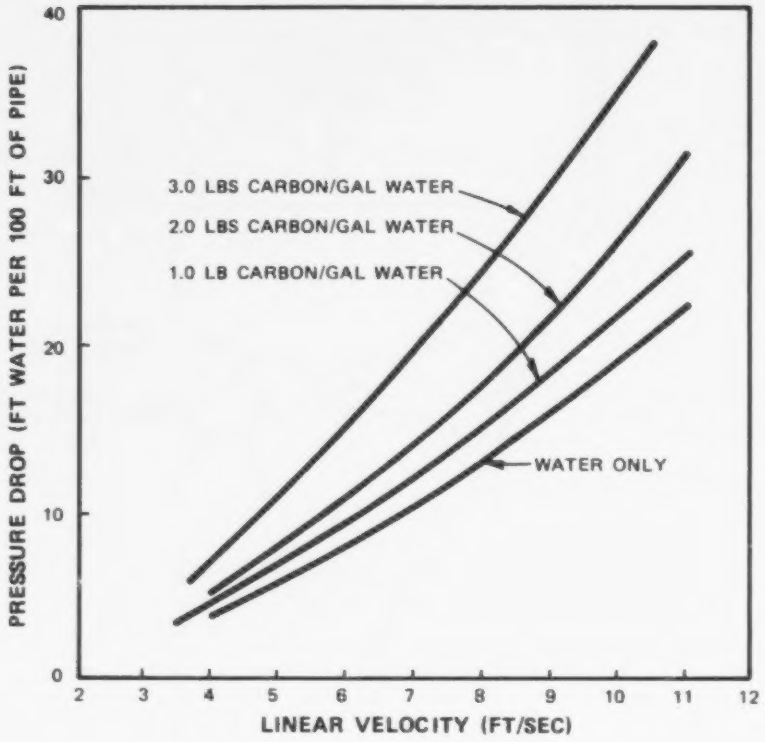


SOURCE: PITTSBURGH ACTIVATED
CARBON COMPANY

FIGURE 3–24

CARBON DELIVERY RATE

(1 INCH PIPE)

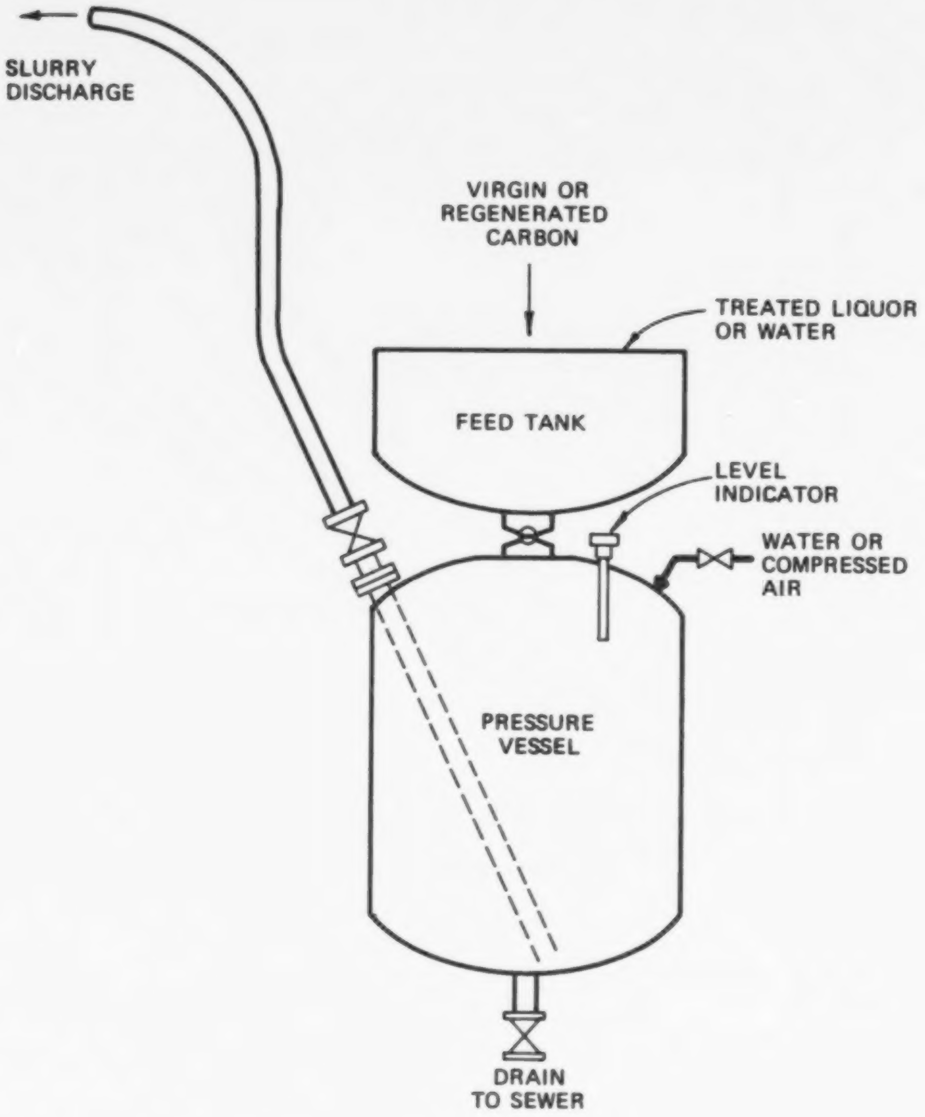


SOURCE: PITTSBURGH ACTIVATED
CARBON COMPANY

FIGURE 3–25

PRESSURE DROP OF CARBON-WATER SLURRIES

(2 INCH PIPE)


SLURRY DISCHARGE
VIRGIN OR REGENERATED CARBON
TREATED LIQUOR OR WATER
FEED TANK
LEVEL INDICATOR
WATER OR COMPRESSED AIR
PRESSURE VESSEL
DRAIN TO SEWER

SOURCE: PITTSBURGH ACTIVATED CARBON COMPANY

FIGURE 3–26

BLOWCASE TRANSPORT SYSTEM

should have extra large suction inlets, a recessed non-clogging type of impeller, and an extra large packing box with seal to protect the shaft from wear. Preferred materials of construction include 316 stainless steel, silicon iron or rubber lining. This is true especially for those components in contact with the abrasive slurry.

The eductor serves the two-fold purpose of mixing carbon and water and of accelerating the transport fluid. It must, of course, have a pumped water supply associated with it to assure pressure and flow. In such an application, the pump may be selected for its use in pumping clean water. In most installations, the spent carbon is transported in excess water, and as much of this water as possible must be removed prior to feeding this material to the regeneration equipment.

Tests have indicated that dewatering of the spent carbon slurry can be successfully accomplished mechanically by use of screens, classifiers, or forced air, or by gravity separation with decanting of the water. Slurries containing 3 to 4 pounds of water per pound of 12 x 40 mesh carbon have been dewatered to 50-60 percent moisture (wet basis) by use of vibrating screens. In existing wastewater installations, slurries have been dewatered to 40-55 percent moisture content by gravity drainage in a tank if sufficient screen area is provided. Normally 10 minutes is sufficient to provide adequate reduction of the moisture content.

The drainage bins should be large enough to provide an adequate source for the controlled feed of the regeneration furnaces. The use of two drain bins will allow for a continuous furnace feed by eliminating a waiting period for drainage to take place. Dewatering screws have also proven to be satisfactory for dewatering. The use of a dewatering screw will eliminate the need for a drain bin, but a spent carbon storage bin is still needed to provide a constant feed to the dewatering screw. The size of the storage and/or drain bin is dependent on the adsorption-regeneration system configuration. With an upflow pulsed or countercurrent system, the storage bin must be large enough to receive the entire slug that is withdrawn at one time. When the contents of a contactor are regenerated as a batch, its contents can be withdrawn as it is regenerated allowing for drainage, or its contents can be transferred to a storage bin making the contactor available to receive regenerated carbon and be placed back on line.

Makeup carbon can either be delivered in bulk or in bags. With the development of modern, economical and efficient methods of handling bulk activated carbon, it is normally less expensive than bagged carbon, particularly if there is a railroad siding at the plant site. If the quantity of makeup carbon is small, the savings of bulk delivery costs over bag delivery must be weighed against the cost of storage facilities and receiving systems required for bulk shipments.

For makeup systems using bagged carbon, the carbon can be introduced into the system by dumping bags of virgin carbon into slurry bins or wash tanks from which it can be transported hydraulically. Bulk carbon can be delivered by rail or truck. With specialized cars or trailers, the carbon is fluidized with air in the carriers and transported pneumatically to storage tanks. If the makeup carbon is stored dry, it can be introduced into the adsorption-regeneration system pneumatically. The air velocity should be between 50 and 100 fps. The solids should occupy 3 to 12 percent of the volume or the solids-to-air mass ratio should be between 30 and 100. If the makeup carbon is stored in a slurry, it can be introduced into the system hydraulically.

Except for upflow expanded beds, both makeup carbon and regenerated carbon must be washed before it is placed in carbon columns in order to remove fine carbon dust, and thus avoid plugging and excessive headlosses in the carbon beds. The wash tank is first filled with water, and then the carbon is introduced and washed with the fines passing out through the screens along with the washwater to plant recycle. Then the wash tank can be pressurized to convey the carbon to the carbon column or other desired point of delivery.

De-fining may require approximately a one-hour carbon wash with backwashing of the wash tank effluent screens about every 15 minutes. Typical makeup carbon and regenerated carbon wash tanks are shown in Figures 3-27 and 3-28.

Once the regenerated carbon is washed, it may be held in the wash tank until it is conveyed directly to the carbon contactors or it may be transported to a regenerated carbon storage bin. The need for regenerated carbon storage bins is dependent on the adsorption-regeneration system configuration.

For a system in which contents of a contactor are withdrawn in a batch with only one "spare" contactor, there must be provisions for storing a volume of carbon to fill one contactor. This storage can be prior to or following regeneration. For a system with two "spare" contactors there is no need for storage in as much as the spent carbon can be withdrawn from one contactor , and as it is regenerated, can be transferred directly to the second "spare". "Spare" contactors refers to contactors not required onstream in the adsorption process. Some upflow contactors are designed so that spent carbon can be withdrawn and makeup carbon added without interrupting normal use of the contactor. The recommended methods for hydraulic loading of granular carbon columns is to employ a blowcase, eductor or centrifugal slurry pump. When these methods are not practical, carbon can be loaded into the column in the dry state provided recommended procedures are followed for column loading.

3.8.2 Hydraulic Loading Procedures

One of the advantages of filling columns hydraulically is that the carbon can be wetted and partially deaerated before it enters the column. This minimizes the possibility of air pockets in the column which lead to channeling. In moving bed systems, the regenerated carbon is sometimes transported to the column in treated effluent. In fixed bed systems

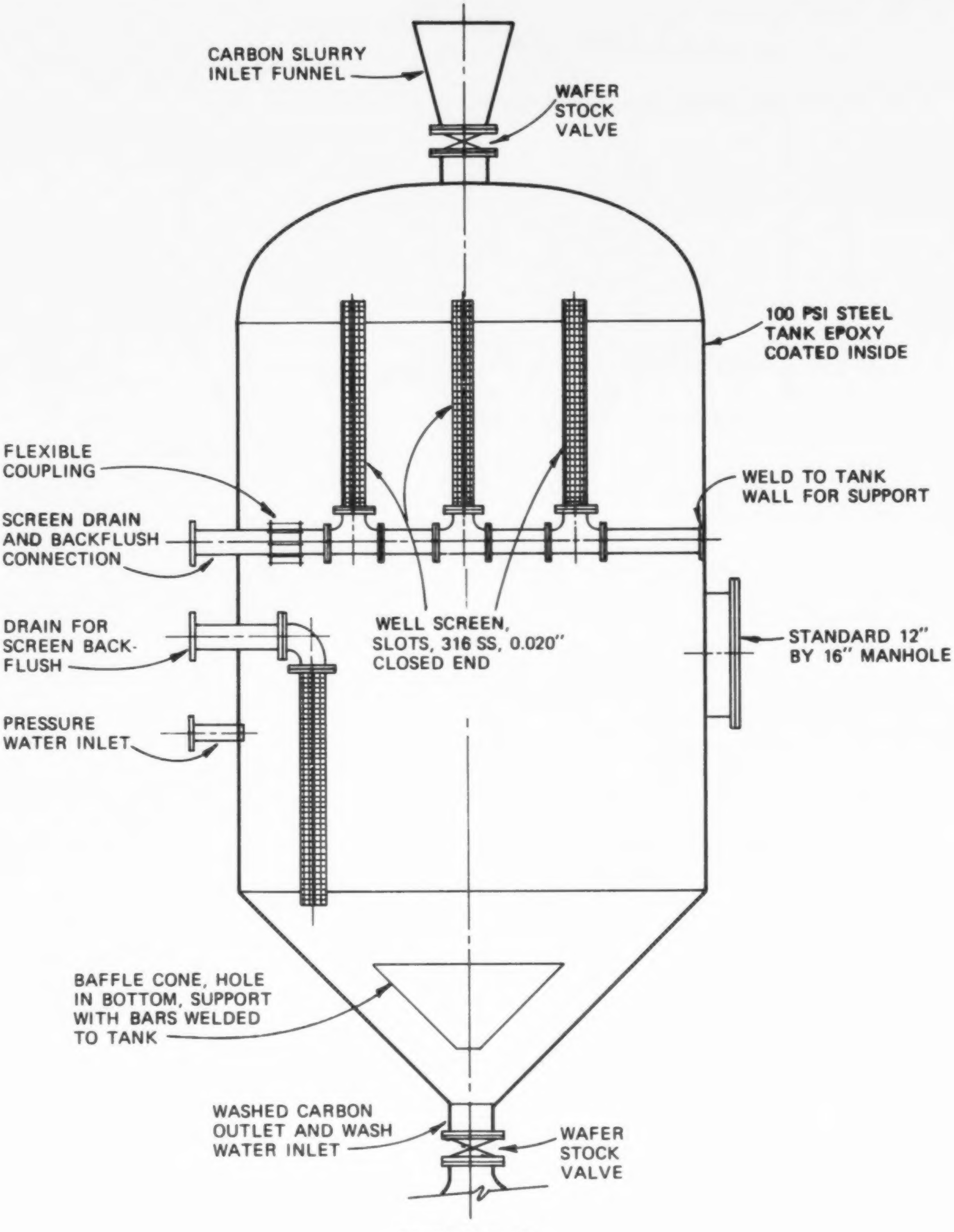

CARBON SLURRY INLET FUNNEL
WAFER STOCK VALVE
100 PSI STEEL TANK EPOXY COATED INSIDE
FLEXIBLE COUPLING
WELD TO TANK WALL FOR SUPPORT
SCREEN DRAIN AND BACKFLUSH CONNECTION
DRAIN FOR SCREEN BACK-FLUSH
WELL SCREEN, SLOTS, 316 SS, 0.020" CLOSED END
STANDARD 12" BY 16" MANHOLE
PRESSURE WATER INLET
BAFFLE CONE, HOLE IN BOTTOM, SUPPORT WITH BARS WELDED TO TANK
WASHED CARBON OUTLET AND WASH WATER INLET
WAFER STOCK VALVE

FIGURE 3–27

REGENERATED CARBON WASH TANK

(FOR 8x30 MESH CARBON)

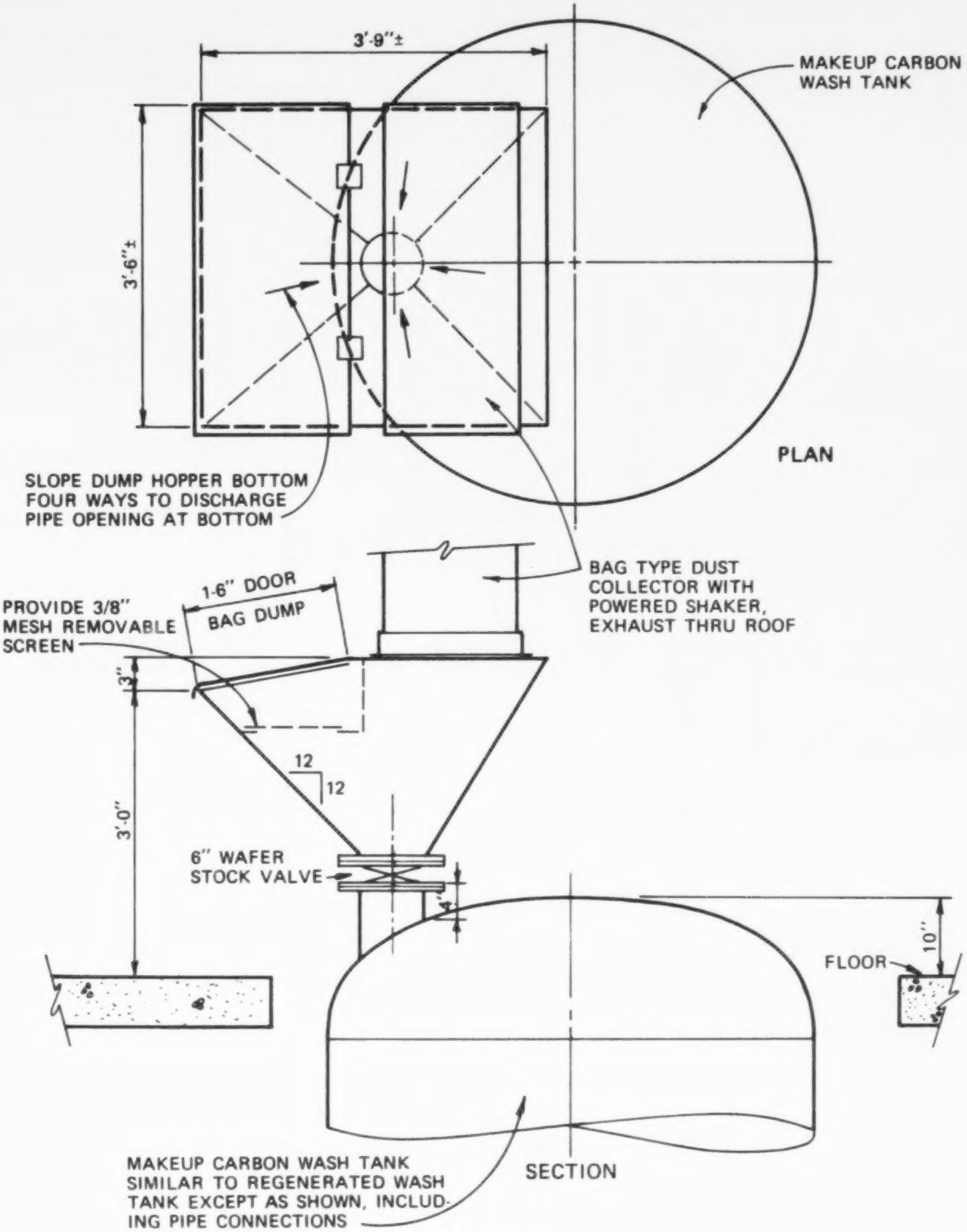

3'-9"±
MAKEUP CARBON WASH TANK
3'-6"±
PLAN
SLOPE DUMP HOPPER BOTTOM FOUR WAYS TO DISCHARGE PIPE OPENING AT BOTTOM
BAG TYPE DUST COLLECTOR WITH POWERED SHAKER, EXHAUST THRU ROOF
1-6" DOOR
BAG DUMP
PROVIDE 3/8" MESH REMOVABLE SCREEN
3"
12
12
3'-0"
6" WAFER STOCK VALVE
4"
10"
FLOOR
MAKEUP CARBON WASH TANK SIMILAR TO REGENERATED WASH TANK EXCEPT AS SHOWN, INCLUDING PIPE CONNECTIONS
SECTION

FIGURE 3–28

MAKEUP CARBON WASH TANK

the use of a carbon-water slurry is usually the simplest and most economical means of moving carbon. Provisions should be made to maintain an adequate carbon-liquid ratio in the transport lines (1 lb carbon per gal liquid).

When the column has been filled with slurry, there will be an excess of water. Therefore, the product discharge valve must be opened or a screened overflow arrangement made in order to discharge the excess liquid during the loading operation.

3.8.3 Piping and Valves

Carbon is an abrasive material and when hydraulically transported will tend to wear the inside of pipes, particularly in elbows, tees, or other changes in direction or in locations where high headloss and excessively turbulent flow are encountered. Long radius elbows should be used for all bends to reduce wear at these points. Experience with unlined straight pipes, however, has indicated very little wear of the inside surfaces of pipes on the straight run after being in service for several years. The piping system should be designed for easy disassembly and for flushing after each slurry transport operation. This requires the use of sufficient cleanouts, flushing connections and drains.

Steel pipes have been used satisfactorily in applications where the slurry transport is not continuous. Steel may also be used when the piping is readily accessible for repair or replacement. More expensive materials or linings such as rubber, saran, glass, polyvinyl chloride and stainless steel may be justified only under special conditions, or in industrial installations where corrosive liquids are encountered.

Valves used in wastewater disposal systems may be classified in several categories, each of which may be further subdivided according to various design options.

Diaphragm (straight way)

Globe

Rotary (ball, butterfly, cone, plug)

Slide (gate valve, shear gate, wafer stock)

Ball check

Swing check

In selecting a valve for installation in a slurry transport line, there are four major considerations: the purpose of the valve, its effectiveness in accomplishing functional requirements, the resistance of the valve to the abrasive effects of slurry transport and the costs. Because of the abrasive nature of carbon slurry, valves in slurry lines must not be used for throttling service or flow control, this must be done on the water supply line. Valves in carbon slurry lines are for shut off or check service only. Globe valve and gate valves normally used in pipelines are not applicable because they will not positively seat due to obstructions by carbon particles on the seat or wear of the seat by the abrasive slurry. Preferred valves to assure positive off and on operations are rotary type such as ball and plug valves. These valves should offer no restriction to slurry transport when in the open position. The diaphragm valve, certain variations of which offer limited restriction of the open passage, has a movable element of flexible rubber, leather or some special composition, which will be worn over a period of use and will require replacement. One valve which has given excellent service is the wafer stock or knife gate valve.

Both swing type and ball check valves are suitable for backflow prevention in slurry pumping. Although the seating face against which the closing device rests is susceptible to abrasive wear and the flow is restricted by the configuration of the valve, there is no acceptable substitute that can achieve the same purpose. If swing checks are used, they may be of a type designed for use in a vertical line to minimize the deposit of carbon particles in the valve seat. They are usually installed in pairs for greater reliability.

Regulation of slurry flow can best be accomplished by throttling the water supply line, as there is no satisfactory valve for throttling flow of the abrasive carbon slurry.

If the carbon slurry piping system is 2 to 3 inches in size, the cost of periodically replacing carbon lines of black steel pipe may be far less than installing a high priced system of glass lined, rubber lined, fiberglass, or other abrasion resistant special pipe.

Automatic operation of carbon-contacting systems might be accomplished using standard equipment. However, it is not required because of the extended lengths of time between operations of the equipment; valves serving separate carbon vessels are usually operated only during withdrawal and replacement of carbon for regeneration, except for occasional flow reversals. Since this occurs only about once every one to two months, it may be best to operate the valves manually, with operator observation and attendance. In downflow arrangements in which the carbon beds act as filters in addition to providing adsorption sites, operation can become more frequent and somewhat complex and automatic valve operation may be desirable.

3.9 Carbon Regeneration Systems

To make granular activated carbon economically feasible for wastewater treatment in most applications, the exhausted carbon must be regenerated and reused. When the plant effluent quality reaches the minimum effluent quality standards or when a predetermined carbon dosage is achieved, spent carbon is removed from the columns to be regenerated.

Closely controlled heating in a multiple hearth furnace is presently the best procedure for removing adsorbed organics from activated carbon. Thus, maximum effort has been concentrated on optimization of thermal regeneration techniques in an atmosphere of limited oxygen and steam.

A typical basic sequence for the thermal regeneration of carbon is as follows:

a. The granular carbon is hydraulically transported (pumped) in a water slurry to the regeneration station for dewatering.

b. After dewatering, the carbon is fed to a furnace (usually of the multi-hearth type) and is heated to 1500 degrees F - 1700 degrees F in a controlled atmosphere which volatilizes and oxidizes the adsorbed impurities.

c. The hot regenerated carbon is quenched in water.

d. The cooled regenerated carbon is washed to remove carbon fines and hydraulically transported to the adsorption equipment or to storage.

e. The furnace off-gases are scrubbed, (the scrubber water is returned to the plant for processing) and may also pass through an afterburner.

A typical carbon regeneration system is shown in Figure 3-29.

The thermal regeneration process itself involves three steps:

a. Drying

b. Baking (pyrolysis of adsorbates), and

c. Activating (oxidation of the residue from the adsorbate).

The total regeneration process requires about 30 minutes: the first 15 minutes is a drying period during which the water retained in the carbon pores is evaporated, a 5 minute period during which the adsorbed material is pyrolyzed and the volatile portions thereof are driven off, and a 10 minute period during which the adsorbed material is oxidized and the granular carbon reactivated.

The theoretical required furnace capacity can be determined simply by multiplying the carbon dosage (in lbs of carbon per million gallons) by the daily flow rate in million gallons per day. This will determine the lbs of carbon per day that must be regenerated. This computation does not allow for furnace downtime or other contingencies that must be considered when actually specifying the furnace size to be installed.

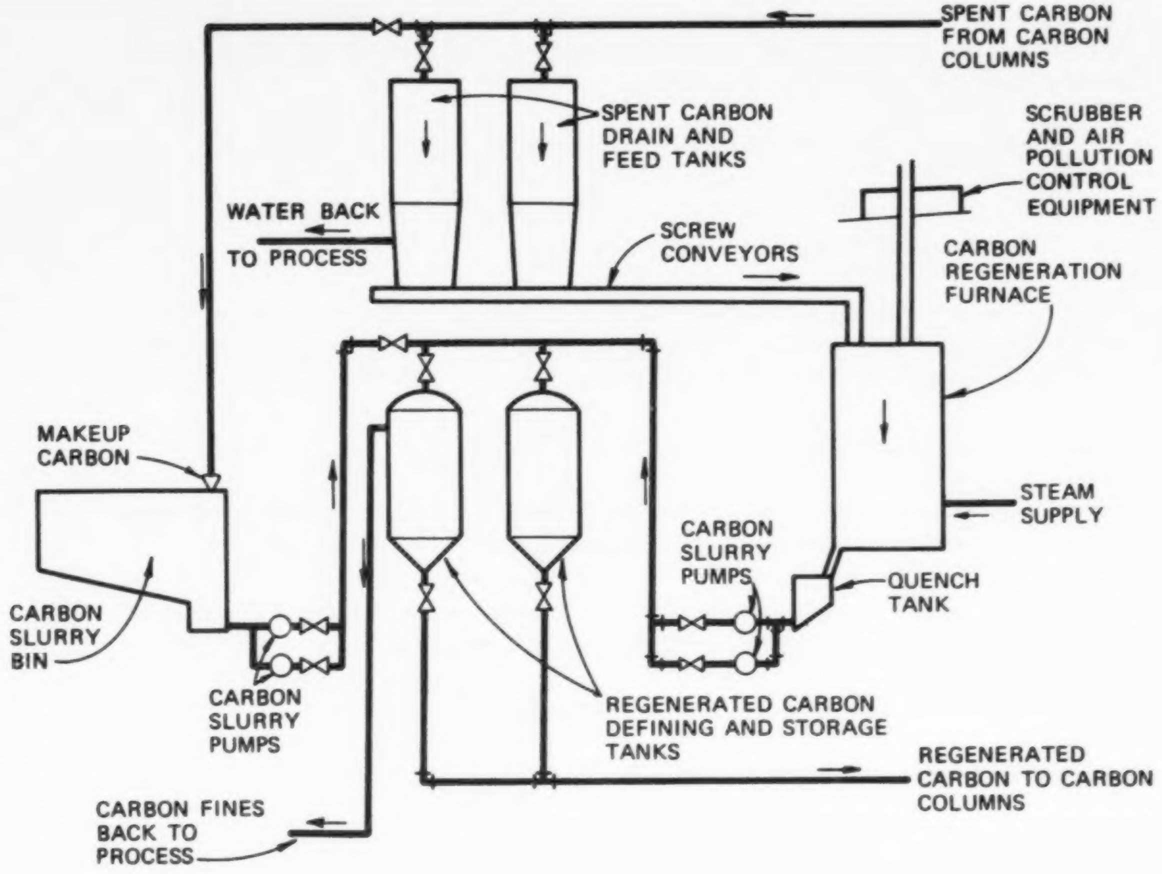

SPENT CARBON FROM CARBON COLUMNS
SPENT CARBON DRAIN AND FEED TANKS
SCRUBBER AND AIR POLLUTION CONTROL EQUIPMENT
WATER BACK TO PROCESS
SCREW CONVEYORS
CARBON REGENERATION FURNACE
MAKEUP CARBON
STEAM SUPPLY
CARBON SLURRY PUMPS
QUENCH TANK
CARBON SLURRY BIN
CARBON SLURRY PUMPS
REGENERATED CARBON DEFINING AND STORAGE TANKS
REGENERATED CARBON TO CARBON COLUMNS
CARBON FINES BACK TO PROCESS

FIGURE 3–29

CARBON REGENERATION SYSTEM SCHEMATIC

An allowance of 40 percent downtime in selecting the furnace size provides a conservative basis for furnace selection.

Multiple hearth furnaces used for regenerating carbon should provide a hearth area of about one square foot per 40 lbs of carbon to be regenerated per day.

The regeneration furnace should be designed so that the hearth temperatures, furnace feed rate, rabble arm speed, and steam addition can be controlled.

The hot gases on the top hearth of the regeneration furnace contain both fine carbon particulates and odorous materials visible as smoke. Since the wet spent carbon enters the top of the furnace near the exit point for the exhaust gases, some of the more volatile adsorbate is removed from the carbon and carried into the atmosphere without being completely oxidized. Both this smoke and the carbon particulates might present air pollution problems if left uncontrolled. Therefore, it is imperative that air pollution control equipment be included in the design of the carbon regeneration furnace. Systems are available and in use which include an afterburner, for removal of smoke and odors, and a wet scrubber or bag filter for removal of particulates. These are designed as integral parts of the furnace installation. Stringent air emission standards have been met by use of a variable-throat Venturi-type scrubber with 20 inch pressure drop. [5]

As carbon is removed from service for regeneration, the spent carbon is usually hydraulically transported to a drain bin. The drained carbon is dried during the first step in a furnace which heats the carbon to less than 212 degrees F. During baking, the temperature increases from 212 degrees F to 1,500 degrees F, by which time adsorbed organics are thoroughly carbonized. This is accompanied by evolution of gases and by the formation of a carbon residue in the micropores of the activated carbon. The objective of this activating step is to oxidize the carbon residue with minimum resultant damage to the basic pore structure, thereby effecting maximum restoration of the original properties of the carbon. The activating gas temperature during this step is about 1,700 degrees F, while the carbon temperatures range from 1,500 degrees F to 1,650 degrees F. Flue gas supplemented by varying amounts of additional steam and limitation of oxygen produces the desired atmosphere. The most important phase of the regeneration process is that of activation, with the critical parameters being carbon temperature, duration of activation, and steam or carbon dioxide concentration in the activating gas mixture. Since most installations use direct-fired multiple hearth furnaces for regeneration, the combustion of natural gas with air provides the required heat, while carbon dioxide, oxygen, and steam, as part of the products of combustion, are the activating agents. Extra steam at approximately one pound per pound of carbon regenerated is supplied. This requires auxiliary steam generating equipment.

With the 6 hearth furnace at South Tahoe, the burners are located on hearths 4 and 6. To maintain the desired carbon temperature, the temperatures on the various hearths are approximately as follows: No. 1, 800 degrees; No. 2, 1,000 degrees; No. 3, 1,300 degrees;

No. 4, 1,680 degrees; No. 5, 1,600 degrees; and No. 6, 1,680 degrees F. It was found that the addition of steam on hearths 4 and 6 gave a more uniform distribution of temperatures throughout the furnace. The effect of steam is to reduce the apparent density and increase the Iodine Number of the regenerated carbon. About 1 lb of steam per lb of dry carbon was used. Figure 3-30 is a drawing of a regeneration furnace showing the main components.

The regenerated carbon is discharged from the bottom of the furnace into a quench tank. Figure 3-31 shows a typical carbon furnace discharge chute. The outlet of the discharge chute is below the water level in the quench tank. The water jets fed by the pressure water supply must be placed to keep the carbon moving in the quench tank to prevent carbon buildup and plugging of the tank's discharge lines. Figure 3-32 is a sketch of a typical carbon furnace quench tank.

Partially dewatered carbon from drain bins can be fed into the furnace by a screw conveyor. The conveyor should be equipped with a variable speed drive so the rate of carbon feed to the furnace can be controlled accurately. The conveyor should be constructed out of a corrosion resistant material. At South Tahoe, a 9-inch screw is used with a 3-inch pitch at the lower end and a 9-inch pitch at the upper (furnace) end (Figure 3-33). The low-pitch, metering section of the screw under the bin runs full of carbon for accurate feed control, and the higher pitch, conveying section runs only partially full to reduce the total driving torque required. If a dewatering bin is not used in the regeneration sequence, a continuous dewatering screw can be used to feed the regeneration furnace. Continuous dewatering screws have proven to be satisfactory for dewatering the carbon to 50 percent moisture. The screw is fairly insensitive to fluctuations in feed conditions up to a maximum capacity.

Regeneration Fuel–The total fuel requirement for the regeneration system is estimated to be 4,250 Btu per lb of carbon regenerated, exclusive of fuel used in the afterburner. This figure is based on the following:

1. 3,000 Btu/lb carbon is required for furnace heat as determined from operating data at South Tahoe and Pomona.
2. 1,250 Btu will generate one pound of steam which is sufficient for one pound of carbon under regeneration, according to South Tahoe data.

The regeneration furnaces in use at South Tahoe and Pomona are both gas fired, and the one at South Tahoe is equipped with propane standby. The heat requirements will not vary substantially if the furnace size is larger than the 54-inch furnace used at South Tahoe. Very little heat is lost in radiation, thus increasing the furnace hearth area to perimeter ratio provides little savings in fuel.

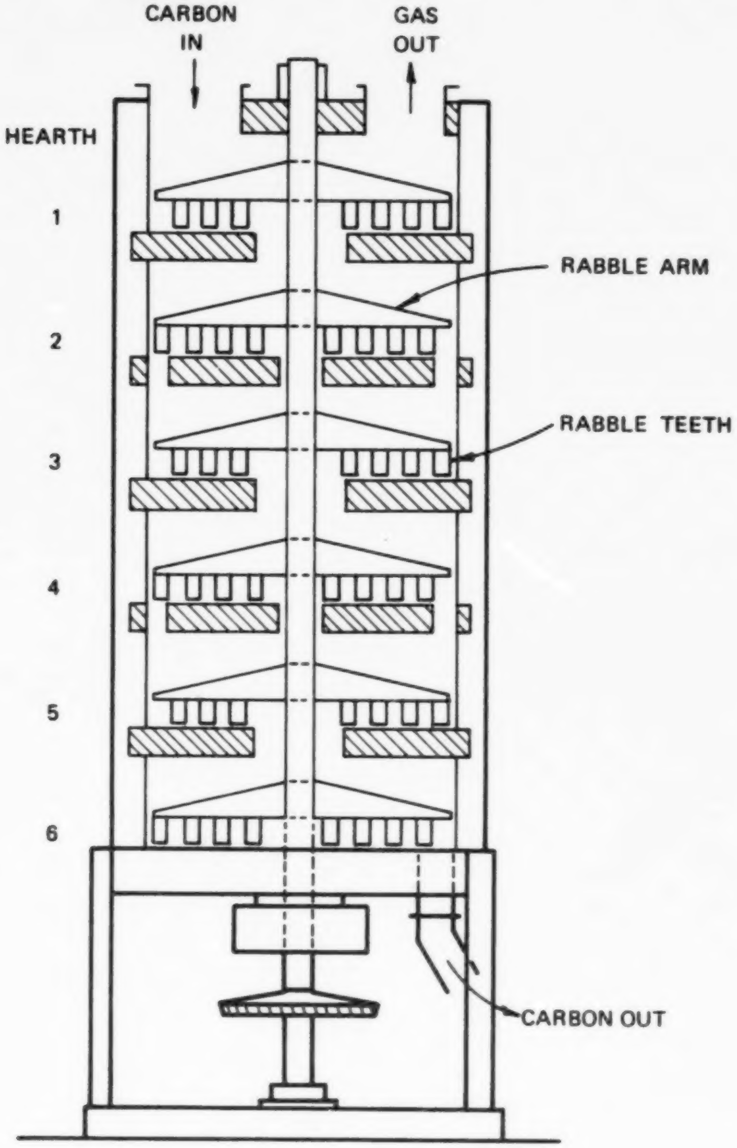

CARBON IN
GAS OUT
HEARTH
1
2
3
4
5
6
RABBLE ARM
RABBLE TEETH
CARBON OUT

FIGURE 3–30

CROSS-SECTIONAL VIEW OF MULTIPLE HEARTH FURNACE

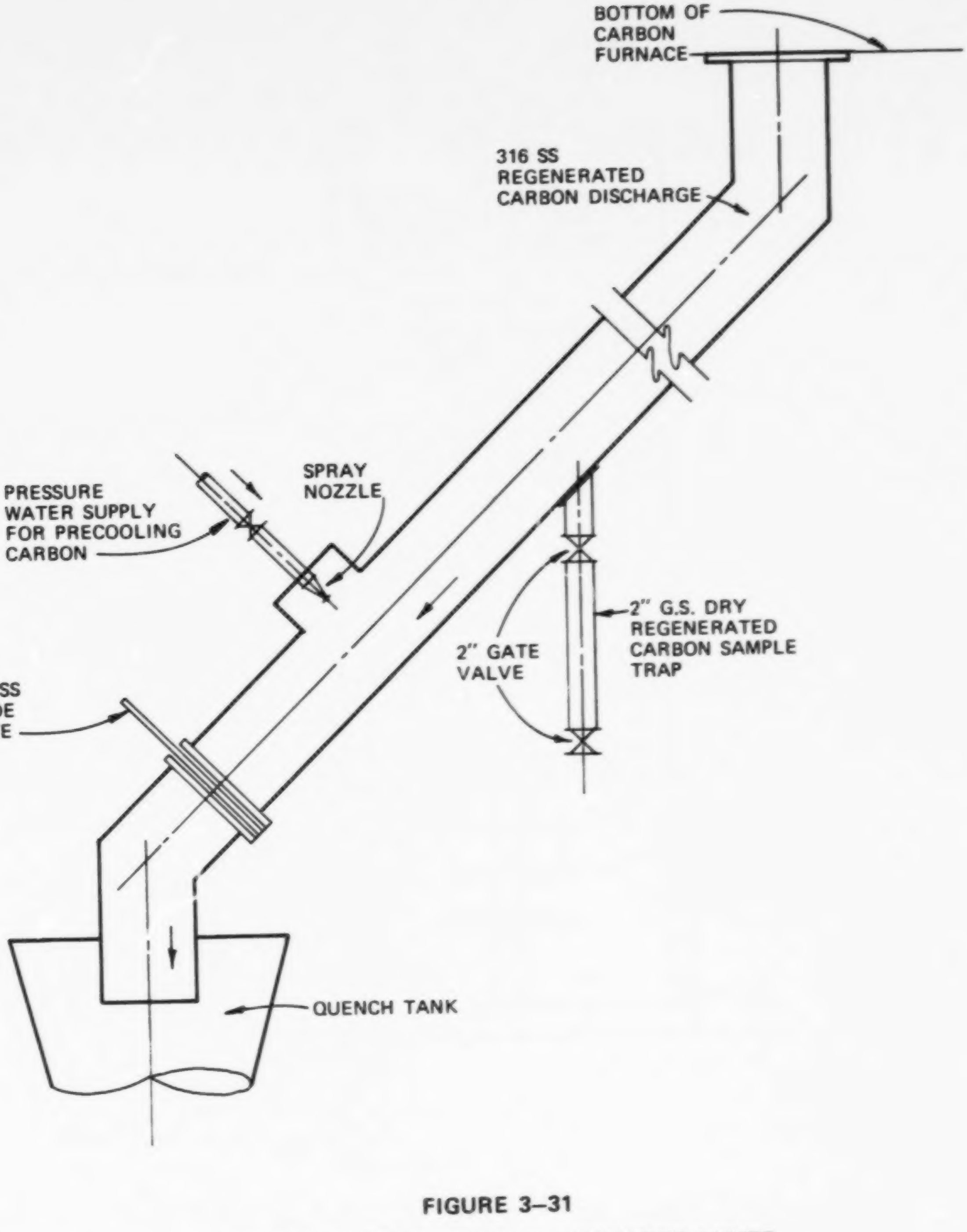
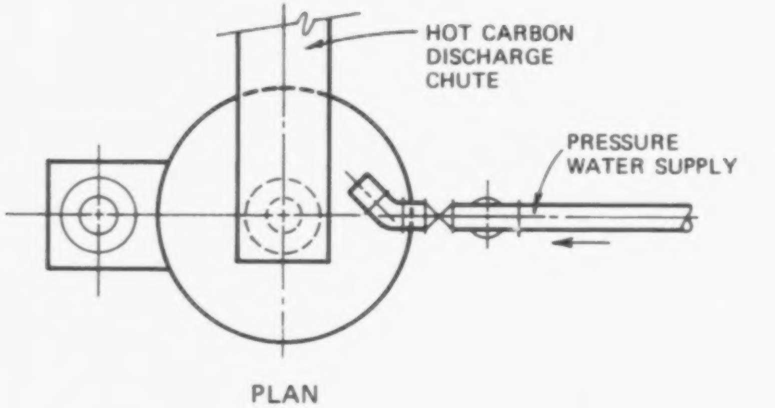

BOTTOM OF
CARBON
FURNACE
316 SS
REGENERATED
CARBON DISCHARGE
PRESSURE
WATER SUPPLY
FOR PRECOOLING
CARBON
SPRAY
NOZZLE
2" G.S. DRY
REGENERATED
CARBON SAMPLE
TRAP
2" GATE
VALVE
316 SS
SLIDE
GATE
QUENCH TANK

FIGURE 3–31

TYPICAL CARBON FURNACE DISCHARGE CHUTE


HOT CARBON DISCHARGE CHUTE
PRESSURE WATER SUPPLY
PLAN

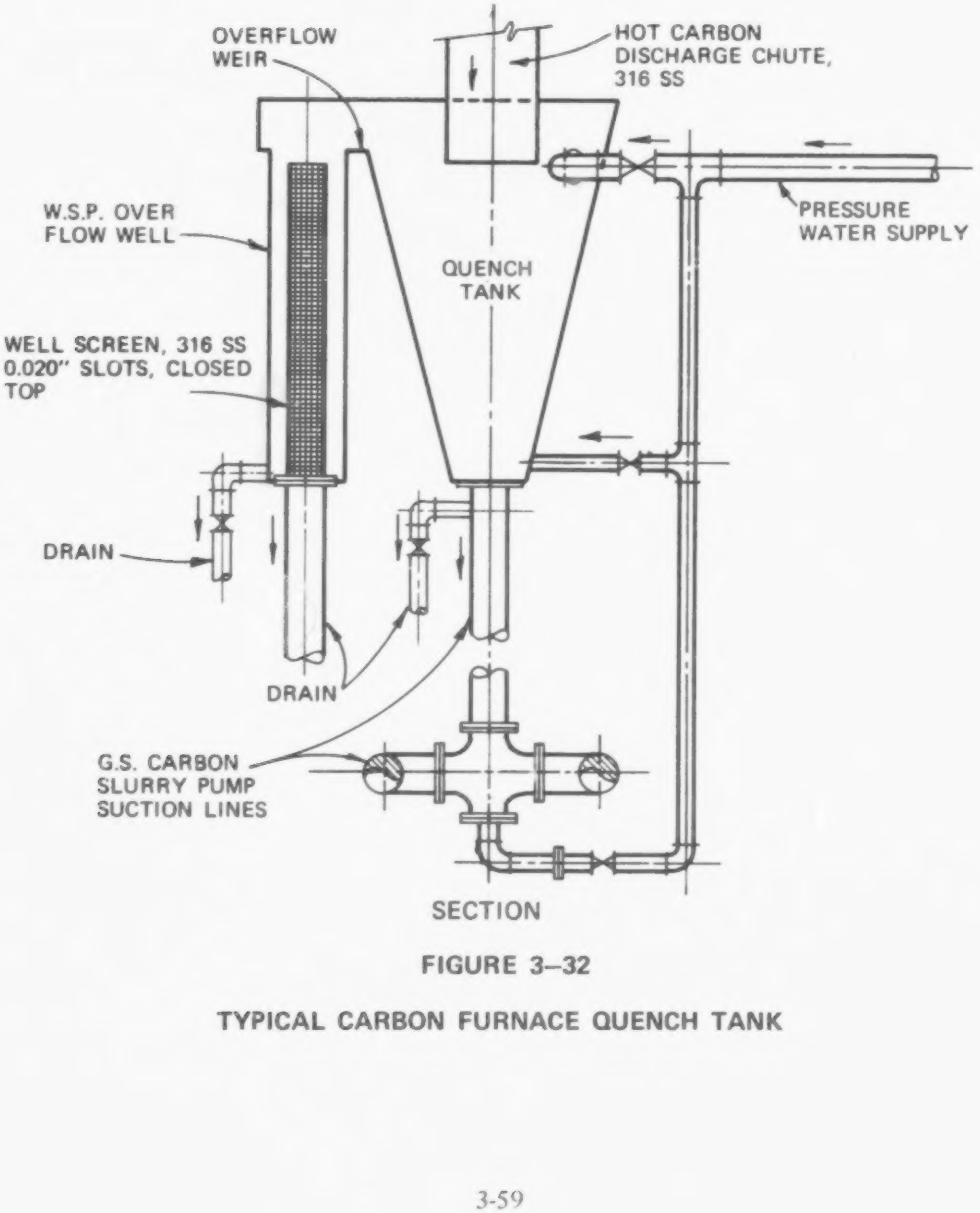
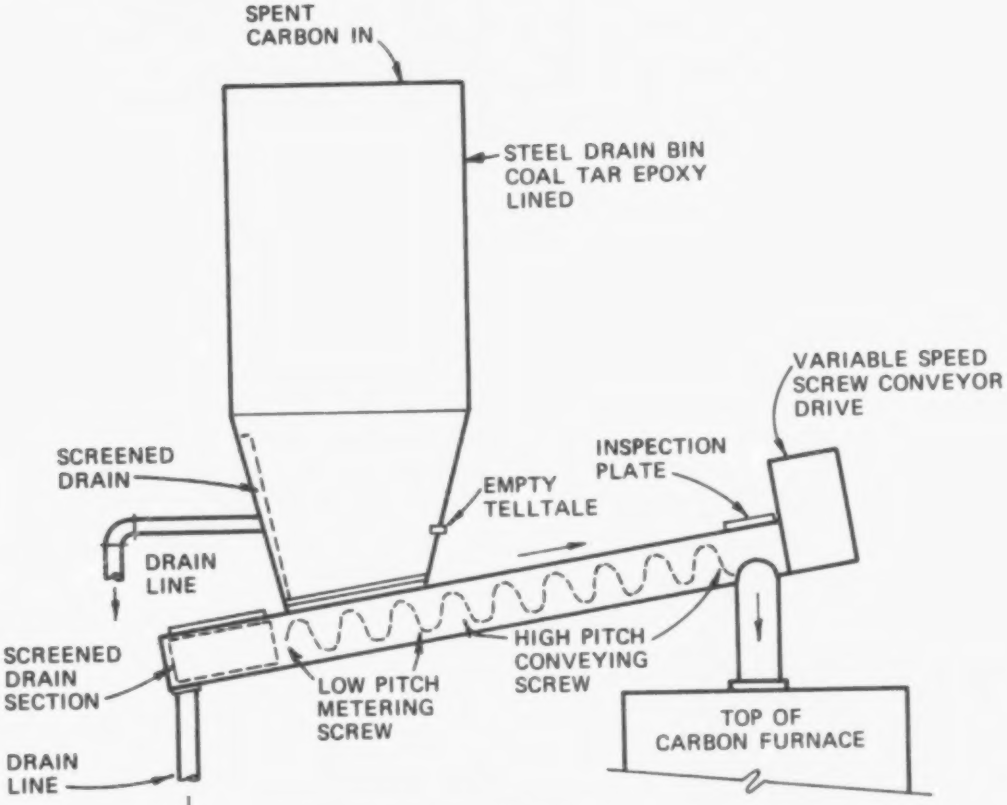

OVERFLOW WEIR
HOT CARBON DISCHARGE CHUTE, 316 SS
W.S.P. OVER FLOW WELL
PRESSURE WATER SUPPLY
QUENCH TANK
WELL SCREEN, 316 SS 0.020" SLOTS, CLOSED TOP
DRAIN
DRAIN
G.S. CARBON SLURRY PUMP SUCTION LINES
SECTION

FIGURE 3–32

TYPICAL CARBON FURNACE QUENCH TANK


SPENT CARBON IN
STEEL DRAIN BIN COAL TAR EPOXY LINED
VARIABLE SPEED SCREW CONVEYOR DRIVE
INSPECTION PLATE
SCREENED DRAIN
EMPTY TELLTALE
DRAIN LINE
SCREENED DRAIN SECTION
HIGH PITCH CONVEYING SCREW
LOW PITCH METERING SCREW
TOP OF CARBON FURNACE
DRAIN LINE

SCREW CONVEYOR AND HOUSING ARE FABRICATED FROM 316 STAINLESS STEEL

FIGURE 3–33

SPENT CARBON DRAIN BIN AND FURNACE FEED ARRANGEMENT

3.10 Recycle Flows

Because tertiary and PCT plants and other plants incorporating carbon treatment are generally aiming at production of water quality better than that of secondary effluent, the handling of internal plant process streams assumes importance. Many, if not all, of these streams must be recycled through part or all of the plant rather than to be directly discharged with the final effluent which would degrade its quality. Since carbon treatment is at or near the downstream end of most flow charts, all of the recycle flows must be added to the anticipated wastewater flows expected on the maximum day. *These recycle flows are significant in amount. They may range from 20 to 35 percent of the maximum daily flow, or even higher in small plants.* Flow from the scrubber on the carbon regeneration furnace alone may be 400-600 gpm. If ignored, recycle flows can seriously overload processes and equipment.

Some recycle flows such as scrubber water are constant in volume. Others such as carbon column backflush water may be high volume, short duration flows, and storage for flow equalization may be necessary. In some cases, if storage is provided, it may be possible to release the recycle flows during off-peak flow periods.

The point at which recycle flows are reintroduced to the process should be considered. Many will go to the head of the plant, others may only require filtration and carbon treatment, and so on. Usually it is advantageous to return the recycled water to the furthest downstream point in the process which will provide the necessary treatment.

Certain recycle flows originate within the carbon adsorption and carbon regeneration portions of the plant. These include: column and surface backwash water; carbon column to waste; transport water from dewatering tanks or screws; overflow from quench tanks; water from de-fining or wash tanks; and exhaust gas scrubber water. Normally the backwash water would be returned either ahead of the filters if they precede the carbon columns or ahead of the chemical clarification step if there are no filters. Scrubber water may be returned to the filter or chemical clarifier influent, along with transport water, overflow from quench tanks, and water from carbon de-fining.

3.11 Monitoring and Controls

3.11.1 Expected Plant Performance

Because tertiary and PCT treatment processes are new to many operators, it is very helpful for the design engineer to report, preferably both in person and by written summary, what performance is expected from the carbon treatment and in carbon regeneration. During plant startup, the designer should conduct appropriate testing programs under actual operating conditions to substantiate predicted process performance and to establish baselines for future plant operations. The report prepared by the design engineer for the plant operator should include the following: various unit design flows, the design influent and effluent qualities, the characteristics of fresh and regenerated carbon, the average time between carbon regenerations, the range of carbon usage rates, and the results anticipated when the plant is operated above or below its rated design capacity.

It is also the design engineer's responsibility to insure that the plant operator understands the functions and utility of the meters, controls, analytical devices, and other instruments installed to monitor and control the plant and the quality of water produced.

3.11.2 Control of Contactor Operation

The operation of any of the types of contactors previously discussed is a simple task, although the series downflow beds introduce some complexities because of the greater number of valves to be operated.

Basically, contactor operation consists of bringing the wastewater to be treated into contact with the carbon at the proper throughput rate until as much of the adsorptive capacity of the carbon is utilized as the capabilities of the installed system will allow. Then, when the plant effluent no longer meets the desired quality standard, some quantity of spent carbon must be removed for regeneration and replaced with an equal quantity of regenerated and makeup carbon.

The plant operator has some control over flow rates and contact times between the wastewater and the carbon by selecting the total number of contactor units which are placed into service at a given plant influent flow. In operation of many plant processes, it is good practice to keep as many units on the line as possible. This reduces unit loadings on the processes and generally improves performance. This is also true to a certain extent in the operation of carbon contacting systems, but there are some exceptions worthy of note. Hydrogen sulfide generation has been a problem in some carbon adsorption installations, particularly those which apply a heavy load of BOD, COD, and SS to the carbon. Time is one important factor in the amount of sulfide produced, so that at low flow periods in plant operation it may be advisable to remove enough contactor units from service to limit the contact period to the design period. In any event, the total flow should be divided about equally among all the contactors which are in service at any one time. This can be done quite easily by measuring the flow by means of a Dall tube and rate-of-flow indicator and adjusting the flows by means of a manually operated butterfly valve. If the control valve is properly sized, valve settings ordinarily do not change with hourly flow variations within a day, and the valves may only require readjustment when flows increase or decrease sufficiently to require a change in the total number of units in service.

Flow adjustment for upflow expanded beds in the service or adsorption cycle requires more attention than that just described. Sufficient minimum flow must be maintained in each column to expand the carbon at least 10 percent. This is not a precisely fixed quantity due to changes in water viscosity due to water temperature changes, change in density of the carbon as it becomes saturated with organics, and changes in density and particle size due to slime growths on the carbon. If the upflow contactor is operated at less than 10 percent bed expansion, solids may accumulate within the bed and cause development of excessive headlosses. If this occurs, it may be necessary to increase the flow to produce an expansion of 10 to 50 percent in the affected unit for a long enough period to flush out the particulate matter. For minor amounts of material, the unit may be kept in service, but if the amount is enough to interfere with maintenance of the desired effluent quality then it may be necessary to go from column to waste for a short time.

Excessive headloss in packed beds may be either in the bed itself or in the top screens of upflow units. If the loss is only in the screens, momentary flow reversal may be effective in clearing the screens of lodged carbon particles and in reducing the headloss. If the headloss is in the bed itself, then full backwashing (50 percent expansion) of downflow beds is necessary. For upflow beds, a temporary increase in the flow rate with the unit on the line in upflow may be sufficient, but periodically flow reversal followed by 10 percent bed expansion in upflow with the unit out of service is required. The frequency of these operations is low, and it is doubtful that automation is warranted, although it might be worthwhile for backwashing of downflow beds used as filters.

Another factor which requires control is the pH of the carbon column influent. Carbon will function satisfactorily at any pH from 6.5 to 9.0, or perhaps even outside this range, and a decrease in pH during a run between carbon replenishments is no problem, but substantial increase in pH can cause desorption, particularly if the bed is nearing exhaustion. In other words, if a bed of carbon has been operating at a pH of 7.0 for several days or weeks and then the pH is raised to 8.5 for several hours, desorption may occur, that is, previously adsorbed materials such as color, odor, COD, BOD, etc. may be released to the column effluent. This is not a common problem or one that is difficult to control, but it is a problem of which the operator must be aware.

The remaining principal item in the control of contactors is the determination of the time to withdraw carbon for regeneration and replace it with regenerated and makeup carbon. There are a number of ways to do this. In starting up a new plant, it may be done initially by observation of effluent COD concentrations. If the value approaches the predetermined maximum (say 10 to 20 mg/l of COD) desired or mandatory value for an appreciable time period of one or two days, then it probably is time to start a regeneration campaign. In upflow contactors, it is usual to withdraw 5 to 10 percent of the carbon from the bottom of each contactor during each regeneration cycle. In downflow contactors, the entire contents of the lead contactor are removed for regeneration and, if there are two beds in series, the second bed is placed in the lead position by changing valve positions accordingly. Once sufficient data is obtained from operation of a particular plant on a given wastewater with the specific treatment provided ahead of the carbon adsorption process, then there are other ways to determine the need to initiate a regeneration cycle. If adequate records of plant operations and laboratory tests are maintained, then experience will show: (1) the required carbon dosage in pounds of carbon per million gallons of column throughput, and (2) the maximum or optimum loading of the carbon particles by the crucial organic being removed (probably COD in the case of domestic wastewaters) in terms of pounds adsorbed per pound of carbon. Some examples may be useful in this regard. The carbon dosage required depends on the strength of the wastewater feed to the carbon columns and the effluent quality required. Some typical carbon dosages which might be expected are:

	Pretreatment	Typical Carbon Dosage, Pounds Per Million Gals.
1.	Tertiary, activated sludge, high-lime (pH = 11) clarification, recarbonation, and mixed-media filtration (average dosage in 5 years of operation at Tahoe = 210).	200 - 400
2.	Secondary plus plain filtration	400 - 600
3.	Physical-chemical (high lime, pH = 11, treatment of raw waste and primary clarification).	1,500 - 1,800

If dosage is to be used as the basis for initiating regeneration, then it should be determined rather precisely for the particular plant in question. This may require at least one year's operation. The above figures are a rough guide only, and may vary widely from place to place even with the same process because of differences in the waters, in plant operation, and in accordance with other variables including climate. Once the dosage is known, then a combination of average COD concentration in the applied water and total flow through the bed will establish the need for transfer of carbon. To use this method, the plant design must include: flow measurement (and possibly flow totalizing and recording) for each carbon column; laboratory equipment for running COD, BOD, color, MBAS, turbidity, and other control tests; means for measuring the level and calculating the volume of carbon in contactors, drain bins, and storage bins; access for inventory of idle or makeup carbon in bags or other storage; and development of forms for recording the movements and quantities of spent, regenerated, and makeup carbon, as well as associated laboratory test results.

3.11.3 Control of Carbon Regeneration

Figure 3-34 shows a typical carbon contacting and regeneration process flow diagram with upflow contactors (packed bed). With the use of expanded upflow contactors, the washing of makeup and regenerated carbon shown in Figure 3-32 may be omitted. For downflow contactors, the regeneration portion of Figure 3-32 still applies; only the contactor and the method of removing carbon from it would change.

Control of the quality of regenerated carbon is performed at the plant by the operator by measuring the apparent density of the regenerated carbon, and later checked by laboratory tests to measure the capacity of the regenerated carbon to adsorb a standard iodine solution which determined the Iodine Number of the carbon. The A.D. (apparent density) of virgin carbon is about 0.48 gm/cc. As carbon becomes saturated with adsorbed organics, the A.D. may increase to 0.50 or 0.52, or more. As the carbon is regenerated, organics are removed, and the carbon loses weight. If properly regenerated, the A.D. will return to 0.48. The A.D. is easily and rapidly determined by weighing a known volumn of carbon. The detailed procedure for performing the A.D. test is given in Appendix B.

In carbon regeneration if the apparent density is greater than 0.49, the carbon is not obtaining enough heat to volatilize a sufficient quantity of organic material. On the other hand, if the apparent density is less than 0.48, the carbon is obtaining too much heat, and carbon is being burned in the furnace.

The A.D. of the regenerated carbon can be varied by changing the following process variables:

1. Temperature is the most critical factor in carbon regeneration; a higher temperature will give a lower A.D. and a lower temperature will give a higher A.D.

2. Carbon feed rate is the next critical factor in carbon regeneration. Increasing the carbon feed rate will increase the carbon depth on the furnace hearths and will reduce the amount of heat supplied to the carbon. This change will give the carbon a higher A.D. Lowering the carbon feed rate will decrease the depth of carbon and increase the amount of heat supplied to the carbon. In turn, the carbon will have a lower A.D.

3. Increasing the steam feed rate will decrease the A.D. Decreasing the steam feed rate will increase the A.D.

4. Furnace drive speed regulates the contact time in the furnace. Increasing the drive speed will reduce the contact time. In practice, this is not as critical as temperature and carbon feed rate.

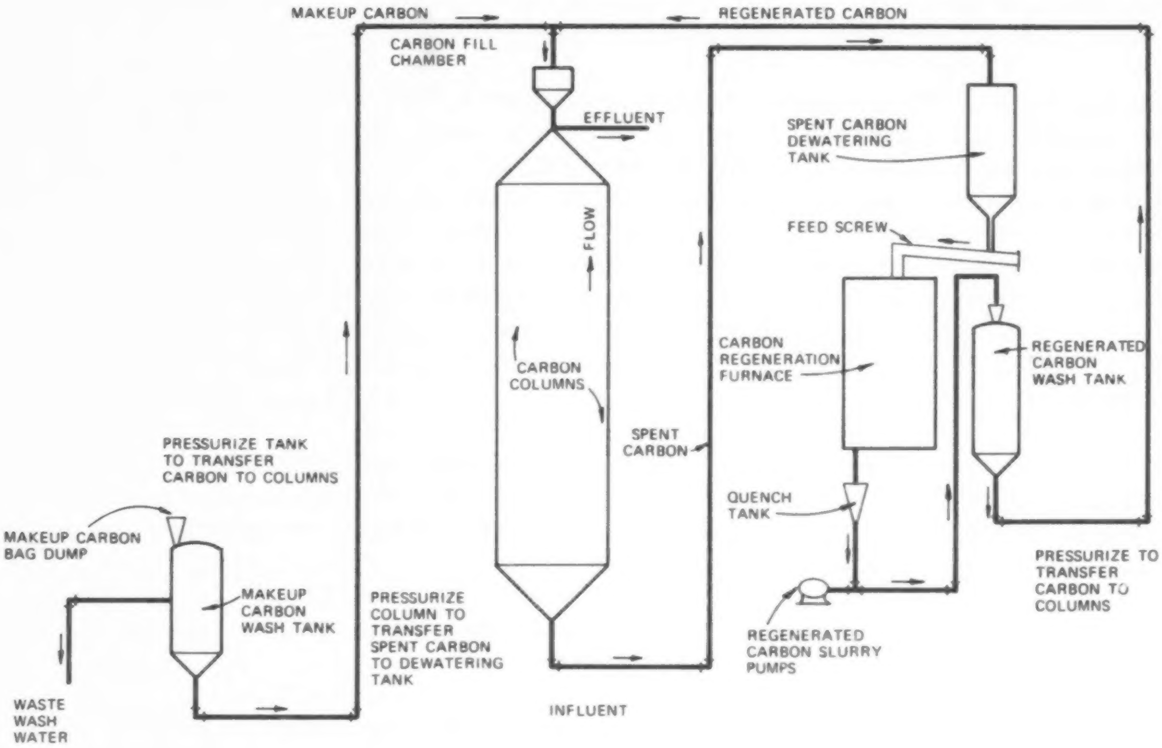

MAKEUP CARBON
REGENERATED CARBON
CARBON FILL CHAMBER
EFFLUENT
SPENT CARBON DEWATERING TANK
FLOW
FEED SCREW
CARBON COLUMNS
CARBON REGENERATION FURNACE
REGENERATED CARBON WASH TANK
SPENT CARBON
PRESSURIZE TANK TO TRANSFER CARBON TO COLUMNS
QUENCH TANK
MAKEUP CARBON BAG DUMP
PRESSURIZE TO TRANSFER CARBON TO COLUMNS
MAKEUP CARBON WASH TANK
PRESSURIZE COLUMN TO TRANSFER SPENT CARBON TO DEWATERING TANK
REGENERATED CARBON SLURRY PUMPS
WASTE WASH WATER
INFLUENT

FIGURE 3–34

CARBON CONTACTING AND REGENERATION –
PROCESS FLOW DIAGRAM WITH UPFLOW CONTACTORS

Do not change more than one process variable per half-hour interval. Typically, there will be about a 5 to 10 percent loss of carbon during each regeneration cycle. The Iodine Number of virgin carbon is about 935, of spent carbon about 580, and of regenerated carbon from 800 to 900. The laboratory test procedure for determining the Iodine Number of carbon is given in Appendix B.

The ash content of carbon may be used to detect any buildup of calcium or other undesirable foreign material. The ash content of virgin carbon is about 5.2 percent. Just prior to the first regeneration, the ash content may increase to about 5.7 percent, and after the first regeneration, when used as a tertiary treatment process, to about 6.4 percent. In subsequent regenerations, there should be little or no change in the 5.7 percent and 6.4 percent values for spent and regenerated carbon. The procedure for determining the ash content of carbon is given in a following section. Somewhat greater ash buildups can be expected if lesser degrees of pretreatment are provided than assumed above.

Carbon may lose some adsorptive capacity upon regeneration, particularly in the first regeneration. Combustion of the adsorbed organics is never really complete. Some ash accumulates in the carbon pores to obscure them and some carbon is burned with the adsorbate, thereby decreasing carbon surface area. The net losses have been measured for the Pomona pilot plant. In a four-stage series downflow carbon contactor, removal of dissolved COD in the lead contactor declined from 89 to 71 percent in two regeneration cycles, but thereafter remained virtually constant at 70 percent. This included the effect of makeup carbon. At Pomona, secondary effluent with no pretreatment was applied directly to the carbon, resulting in application of particulate matter to the carbon which may have contributed to this loss in capacity. At South Lake Tahoe, where the wastewater receives a high degree of pretreatment prior to application to the carbon, removal of COD has not shown a decreasing trend. The removals of about 50 percent COD achieved initially with virgin carbon were also achieved with carbon subjected to four regeneration cycles.

Several controls must be provided for operation of the furnace and its auxiliaries. The rate of spent carbon feed into the furnace determines the residence time of carbon in the furnace which affects the degree of regeneration accomplished. The temperatures on each hearth must be set at the desired value. Once set they should be automatically controlled. The furnace atmosphere is controlled by the draft regulator, burner settings, and steam addition. Draft controls should be automated, and the temperatures on each hearth continuously recorded. Temperatures on the various hearths of a six hearth furnace should be about as follows: No. 1, 800 degrees; No. 2, 1,000 degrees; No. 3, 1,300 degrees; No. 4, 1,680 degrees; No. 5, 1,600 degrees; and No. 6, 1,680 degrees F.

A proportional flowmeter should be provided in each of the air-gas mixture lines to the burners to insure a constant percentage of excess oxygen. In addition, provision should be made so that steam can be added as required.

An ultraviolet scanner should be provided on each of the burners. Then in case of a flame-out, the furnace is automatically shut down. Other safety features which should automatically shut down the furnace are: high or low gas pressure, high combustion air pressure, low scrubber water pressure, high stack gas temperature, and draft fan and shaft cooling air fan, which should be on a standby power circuit to avoid possible damage to the furnace rabble arms in the event of an electrical outage.

3.12 Corrosion and Abrasion Control

Dry carbon and carbon in water slurry is not corrosive. Carbon slurries will drain by gravity to about 40 percent moisture in about 10 to 15 minutes time. It retains this moisture for several weeks under normal storage conditions not subject to forced draft or heating. Partially dewatered carbon is extremely corrosive and under conditions of continuous exposure may produce pits in unprotected mild steel plant by electrolytic corrosion at a rate as high as 1/4-inch of depth per year. Steel can be protected by use of a good coal-tar epoxy paint. A minimum of 3 coats to a total thickness of 10 to 24 mils is recommended. The coating process must be rigidly supervised, inspected, and tested to assure that a continuous coating of the epoxy is obtained. Steel tanks also can be protected by installation of a properly designed cathodic protection system. However, a very liberal extra thickness of steel (about 3/16-inch) should be allowed for corrosion above pressure or other structural requirements. Stainless steel (304 or 316) is a good but expensive material to use in contact with moist carbon. Fiberglass tankage is also a satisfactory approach.

Present engineering practice appears to favor the use of mild steel protected with coal-tar epoxy for carbon contactors, dewatering bins, wash tanks, and quench tanks; the use of stainless steel for conveyors moving spent carbon to the regeneration furnace and for screens in the carbon system; and the use of black steel pipe for carbon slurry lines.

Abrasion of pipelines by carbon slurry is a factor to be considered. However, experience to date indicates that black steel will have a service life in excess of 10 years, so that it may be less expensive to replace steel lines as required rather than to install pipelines of stainless steel or with linings of glass or rubber. Abrasion is maximum at bends so that it is helpful to use long radius fittings at changes in direction of flow and to use extra heavy elbows and tees. Rubber or ceramic lined impellers are recommended for carbon slurry pumps.

3.13 Additional Reading

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13. Weber, W. J., Hopkins, C. B., and Bloom, R. *Physicochemical Treatment of Wastewater.* Journal WPCF, p. 83, (Jan., 1970).

3.14 References

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3. Directo, L. S., *Monthly Reports on the Pomona Pilot Plant.*

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5. *Advanced Waste Water Treatment as Practiced at South Tahoe.* A report by the South Tahoe Public Utility District for EPA (Project WPRD 52-01-67, 1971).

CHAPTER 4

CARBON EVALUATION AND SELECTION

4.1 Introduction

The proper use of activated carbon as a unit process in the treatment of wastewater requires the selection of an appropriate carbon and mode of operation. The selection of an appropriate carbon for wastewater treatment requires a general understanding of the physical properties together with the performance of certain analytical, comparative procedures.

Before selecting a particular carbon for evaluation, both the characteristics of the wastewater to be treated and the effluent requirements must be known.

The most important determinations in laboratory and pilot tests are: (1) the treatability of the waste by carbon, and (2) development of design criteria. The performance of various types of commercial carbons is the subject of some debate; however, the performance of alternate carbons can be estimated from tests with pilot scale contactors. The physical properties of activated carbon are also important, particularly those properties related to its resistance to attrition losses from handling and regeneration.

4.2 Wastewater Characterization

To best utilize the adsorptive properties of a particular activated carbon, it is necessary to know the specific wastewater characteristics. In general, activated carbon is exceptionally suited for the adsorption of dissolved organics. Dissolved organics have been operationally defined as those which pass through a 0.45 micron membrane filter. There are two types of dissolved organics: biodegradable and refractory. Biodegradable dissolved organics are defined as those that are broken down by biological action such as in an activated sludge system. Refractory dissolved organics are defined as those which are not amenable to biological action and remain in solution in the effluent from a biological treatment system.

Biodegradable organics can be measured by the BOD test, but this test is of no value in determining the quantity of refractory organics. A test that measures the total oxidizable organic matter must be used, such as the TOC (total organic carbon) or the COD test. It then follows, that the BOD test is of little value in analyzing the adsorptive properties of activated carbon. The total organic carbon test is perhaps the quickest and most reliable test to be used in evaluation of activated carbon. There are several organic carbon analyzers on the market and all are relatively expensive. The COD test, however, can also be used for an adequate evaluation of the adsorptive properties of activated carbon.

Specific organic waste constituents such as those from industrial processes can be identified using various analytical techniques, such as spectroscopic, spectrophotometric, or chromatographic methods.

There are several inorganic and environmental parameters which may affect the evaluation of activated carbon, namely: pH, temperature, and suspended solids. Decreasing pH and increasing temperature increases the adsorptive characteristics of activated carbon, therefore these two parameters should be held constant during the evaluation procedures. Also, desorption may occur at pH values above 9.0 and adsorption is adversely affected at this high pH.

Suspended solids may affect adsorption and interfere with analytical procedures, therefore samples should be filtered prior to conducting tests. The effects of suspended solids on carbon column operation were discussed in Chapter 2.

4.3 Carbon Evaluation Procedures

With the development of a basic understanding of how and what activated carbon will adsorb, together with a general knowledge of waste characteristics, the next step is to evaluate and select a carbon best suited for a particular purpose.

The suppliers of activated carbon generally provide a table of quality control parameters for their products as shown in Table 2-1. Only a few of the parameters listed by the carbon suppliers are of value in terms of comparing competing activated carbons. Some of the appropriate physical properties that may be used to select one or several carbons for further evaluation are as follows:

1. Surface area–Adsorption is a surface phenomenon, so surface area is a general criteria for the capability of a particular carbon for adsorption.

2. Apparent density–This property is of little value in initial evaluation and selection of an activated carbon, but is very useful as one of the measures of successful regeneration. Apparent density measurement is a simple test, and the density of saturated carbon relative to the density of regenerated carbon indicates the degree of regeneration accomplished.

3. Bulk density–Useful in determining the volume requirements of a carbon column after the contact time requirements have been established.

4. Effective size, mean particle diameter and uniformity coefficient–Measures of the gradation of carbon particle size which are important in evaluating headloss in flow through granular beds.

5. Pore volume–A measure of the total macropore and micropore volume of the carbon which can be of some value in the selection and application of an activated carbon for a specific waste constituent relative to molecular weight. However, there are other more direct measures of the ability of an activated carbon to adsorb different molecular weight substances which will be discussed shortly.

6. Sieve analysis–Very useful in checking carbon production, in checking conformance of purchased carbon to specifications, and in evaluating the effects of plant carbon handling procedures on carbon attrition.

7. Abrasion number–Of limited usefulness at present because the equipment used for testing is unreliable and tests are not reproducible. If the testing procedure is made more reliable, this number may become helpful in evaluating the ability of a carbon to withstand attrition.

8. Ash percent–Indicative of the raw material and manufacturing process used in the manufacture of a particular activated carbon.

9. Moisture as packed, maximum percent–Useful only for shipping and manufacturing purposes.

10. Iodine number–Can be correlated with the ability of an activated carbon to adsorb low molecular weight substances. This value is determined by a relatively easy test and is used widely to determine the restoration of adsorptive capacity upon regeneration.

11. Molasses number, molasses value and molasses decolorizing index–Can be correlated with the ability of an activated carbon to adsorb high molecular weight substances from some liquids, but has not been particularly useful to date for wastewater.

12. Pore size distribution (not usually listed by suppliers in their table of quality parameters)–Characterizes the pore structure which has a great influence on both equilibrium and rate of adsorption. Pore size distributions in the size range of 20-2,000 Angstroms are calculated from nitrogen adsorption isotherms. Pore size distributions are useful for selecting carbons which have high adsorptive capacities for particular types of molecules.

The technical evaluation of activated carbons is best served by providing procedures for the determination of adsorption rate and capacity together with a determination of the ability of each carbon to withstand a specified level of mechanical attrition. Unfortunately, at present, it appears that plant scale experience over a considerable period of time is the only reliable means of predicting the durability of a carbon with respect to mechanical attrition losses, although some very fragile carbons can be identified as unsuitable in the laboratory or brief pilot tests. The ability of granular carbon to withstand handling and slurry transfer is of paramount importance in wastewater treatment. Excessive attrition losses create carbon fines to an extent that intolerable headlosses occur in flow through the beds with catastrophic results in plant operation. Some good way to determine the ability of a carbon to withstand handling must be developed for laboratory use, so that new products can be fairly evaluated without waiting for long term plant trials, but at the moment reliance on the experience in operating plants is the only safe way to proceed.

4.4 Adsorption Isotherms

The adsorption isotherm is the relationship, at a given temperature and other conditions, between the amount of a substance adsorbed and its concentration in the surrounding solution. If a color adsorption isotherm is taken as an example, the adsorption isotherm would consist of a curve plotted with residual color in the water as the abscissa, and the color adsorbed per gram of carbon as the ordinate. A reading taken at any point on the isotherm gives the amount of color adsorbed per unit weight of carbon, which is the carbon adsorptive capacity at a particular color concentration and water temperature. In very dilute solutions, such as wastewater, a logarithmic isotherm plotting usually yields a straight line. In this connection, a useful formula is the Freundlich equation which relates the amount of impurity in the solution to that adsorbed as follows:

$$x/m = kC^{1/n}$$

where:

x = amount of color adsorbed
m = weight of carbon
k and n are constants
C = unadsorbed concentration of color left in solution

in logarithmic form:

$$\log x/m = \log k + 1/n \log C$$

in which $1/n$ represents the slope of the straight line isotherm.

From an isotherm test, it can be determined whether or not a particular degree of organic removal can be effected by adsorption alone. It will also show the approximate adsorptive capacity of the carbon for the application. Isotherm tests also afford a convenient means of studying the effects of pH and temperature on adsorption. Isotherms put a large amount of data into concise form for ready evaluation and interpretation. Isotherms obtained under identical conditions using the same test solutions for two test carbons can be quickly and conveniently compared to reveal the relative merits of the carbons.

As mentioned previously, the Iodine Number and the Molasses Number also give an indication of the adsorptive capacity of a carbon. The Iodine Number is the milligrams of iodine adsorbed from a 0.02 N solution at equilibrium under specified conditions. The Molasses Number is an index of the adsorptive capacity of the carbon for color bodies in a standard molasses solution as compared to a standard carbon. The procedures for determining the Iodine and Molasses Numbers are found in the appendix. These tests are generally used for screening purposes.

As discussed earlier in Chapter 2, since granular carbon columns are dynamic systems, not only are the equilibrium adsorption properties of the carbon important, but also the rates of adsorption illustrated by Figure 4-1. Figure 4-1 shows breakthrough curves of a carbon as obtained by passing a fluid containing an adsorbable substance through a packed bed or carbon. The concentration of the adsorbable substance in the effluent stream from the bed is plotted against the volume of fluid passed through. In Figure 4-1 the breakthrough curve for Carbon E is much steeper than that for Carbon F. This will occur when the rate of adsorption for Carbon E is much greater than that for Carbon F. Generally speaking, greater rates for adsorption are desired for maximum efficiency of the carbon. In actual use, operation is discontinued when the effluent concentration reaches an unacceptable value. The carbon with the steepest breakthrough curve will, therefore, have the longest service life even though the capacity of the carbons at equilibrium may be the same or even higher. Thus, for selecting carbons and designing adsorption systems, the rate of adsorption as reflected in the breakthrough curves, is an important consideration.

Figures 4-2 and 4-3 are presented to illustrate the interpretation of adsorption isotherms. In Figure 4-2, the isotherm for Carbon A is at a high level and has only a slight slope. This means that adsorption is large over the entire range of concentrations studied. The fact that the isotherm for Carbon B in Figure 4-2 is at a lower level indicates proportionally less adsorption, although adsorption improves at higher concentrations over that at low concentrations. An isotherm having a steep slope indicates that adsorption is good at high concentrations, but much less at low concentration. In general, the steeper the slope of its isotherm, the greater the efficiency of a carbon in column operation. In Figure 4-3, Carbon D is better suited to countercurrent column operation than Carbon C. It has a higher capacity at the influent concentration, or more reserve capacity. Carbon C in Figure 4-3 would be better than Carbon D for batch treatment. The procedures for performing an adsorption isotherm are found in the appendix.

4.5 Pilot Carbon Column Tests

Although the treatability of a particular wastewater by carbon and the relative capacity of different types of carbon for treatment may be estimated from adsorption isotherms,

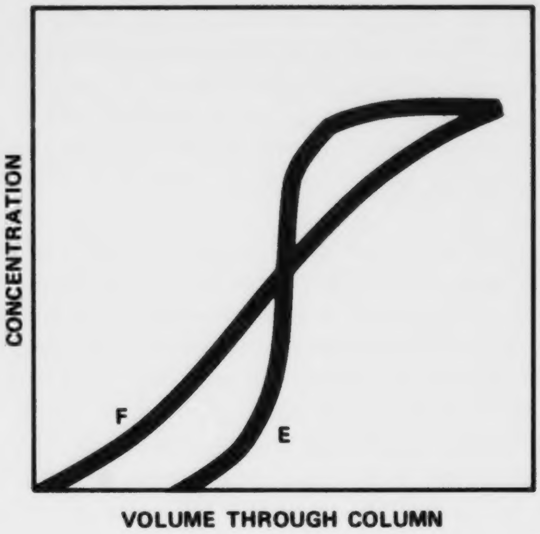


FIGURE 4–1
TYPICAL BREAKTHROUGH CURVES

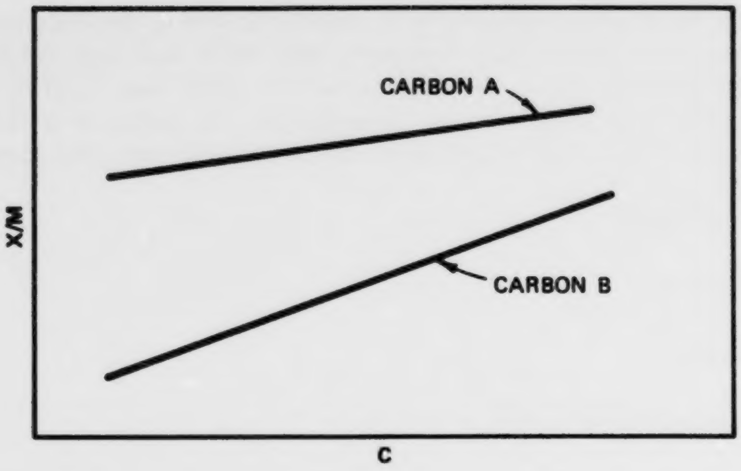


FIGURE 4–2

ADSORPTION ISOTHERM, CARBON A AND B

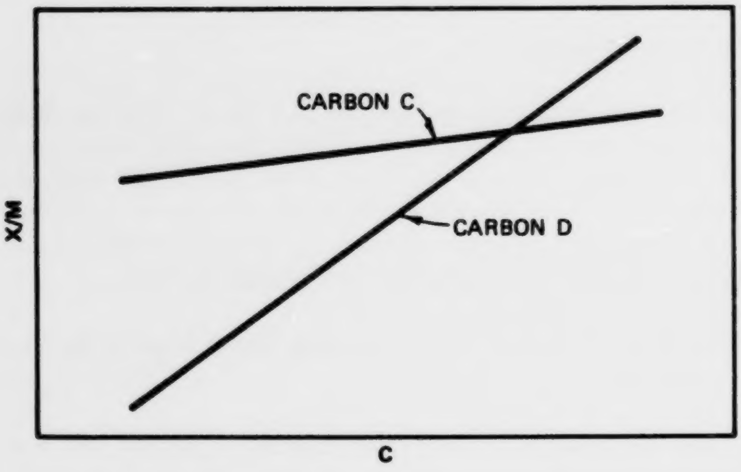


FIGURE 4–3

ADSORPTION ISOTHERM, CARBON C AND D

carbon performance and design criteria are best determined by pilot tests. Adsorption isotherms are determined in a batch test and the treatment of wastewater by granular activated carbon most often is effected in a continuous system involving packed beds similar to filtering operations in waste treatment. Also, batch tests such as isotherms do not measure the potential effects of biological activity which may occur in a column. Pilot tests provide much more accurate estimates of the performance that can be expected in a full-scale unit. Information which can be obtained from pilot tests includes:

1. Type of carbon.
2. Contact time.
3. Bed depth.
4. Pretreatment requirements.
5. Carbon dosage in terms of pounds carbon per million gallons of wastewater or pounds organic material removed per pound of carbon.
6. Breakthrough characteristics.
7. Affect of biological activity including possible extension of the carbon capacity as well as potential deleterious effects such as generation of hydrogen sulfide.
8. Headloss characteristics.

Pilot carbon column tests are performed for the purpose of obtaining design data for full-scale plant construction. What information from pilot plant studies is needed for plant design? It is assumed that one or two carbons have been selected which are effective in treating the particular wastewater, since this can be done by laboratory evaluation as already discussed. It is not necessary to run pilot column tests to reach this point. Pilot column tests make it possible to do the following things:

1. Compare the performance of two or more carbons under the same dynamic flow conditions.
2. Determine the minimum contact time required to produce the desired quality of carbon column effluent, which is the most important of all design factors.
3. Check the manufacturer's data for headloss at various flow rates through different bed depths.
4. Check the backwash flow rate necessary to expand the carbon bed for cleaning purposes.

5. Establish the carbon dosage required, which will determine the necessary capacity of the carbon regeneration furnaces and auxiliaries.

6. If the overall process or plant flow sheet has not been firmly established, check the effect of various methods of pretreatment (influent water quality) upon carbon column performance, carbon dosage and overall plant costs.

7. Evaluate the practical advantages and disadvantages that cannot be evaluated by reading the experiences of others, for alternates such as use of upflow or downflow carbon columns or the particle size of carbon to be used.

Figures 4-4 and 4-5 are schematic flow diagrams of upflow and downflow pilot carbon columns. Details of construction of carbon column pilot plants are described in several publications and are more or less apparent in Figures 4-4 and 4-5.

In all of the pilot plant tests, the pH and temperature should be observed to be certain that they correspond to the values for the full-scale plant operation, since pH and temperature can influence carbon treatment.

The first item among the things to be learned from pilot tests is a comparison of the different carbons tested. This item overlaps to some extent all of the others listed above, for they all may affect the selection of the carbon. However, the first item is aimed principally at gathering data for the plotting of breakthrough curves. These curves are obtained by passing the water containing the substances to be adsorbed through a column of carbon. The concentration of the adsorbable substance in the column effluent is plotted as the ordinate against the volume of water treated as the abscissa. As was mentioned previously, breakthrough curves will determine the service life of a particular carbon as applied to specified conditions.

The pilot test results will also allow a determination of the carbon dosage in terms of pounds of carbon per million gallons of wastewater. Obviously, the dosage will vary with the kind and concentrations of impurities contained in the wastewater. More importantly, the dosage may vary from 200-1,800 lb/million gallons depending upon the degree of pretreatment provided for the wastewater before its application to the carbon and the final effluent quality required.

In evaluating pilot column results, an understanding of the "wave front" concept is useful (see Figure 4-6). As carbon becomes saturated, the zone of adsorption moves downward (in the case of the downflow contactors) with only a gradual increase in the concentration of organics in the carbon effluent, until this zone reaches the discharge point in the column. At this time the organic concentration increases rapidly until it is equal to the influent concentration.

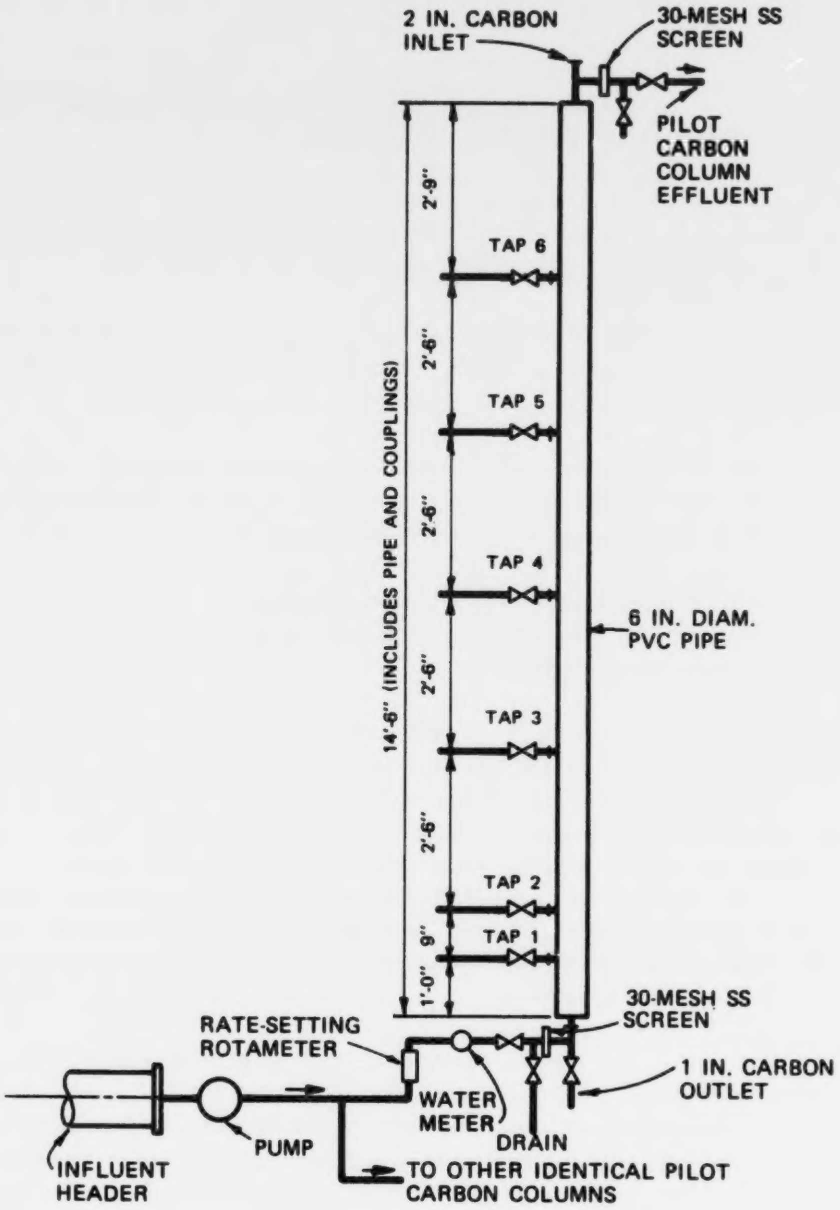

2 IN. CARBON
INLET
30-MESH SS
SCREEN
PILOT
CARBON
COLUMN
EFFLUENT
2'-9"
TAP 6
2'-6"
TAP 5
14'-6" (INCLUDES PIPE AND COUPLINGS)
2'-6"
TAP 4
6 IN. DIAM.
PVC PIPE
2'-6"
TAP 3
2'-6"
TAP 2
9"
TAP 1
1'-0"
30-MESH SS
SCREEN
RATE-SETTING
ROTAMETER
1 IN. CARBON
OUTLET
WATER
METER
DRAIN
PUMP
INFLUENT
HEADER
TO OTHER IDENTICAL PILOT
CARBON COLUMNS

FIGURE 4–4

UPFLOW PILOT CARBON COLUMN

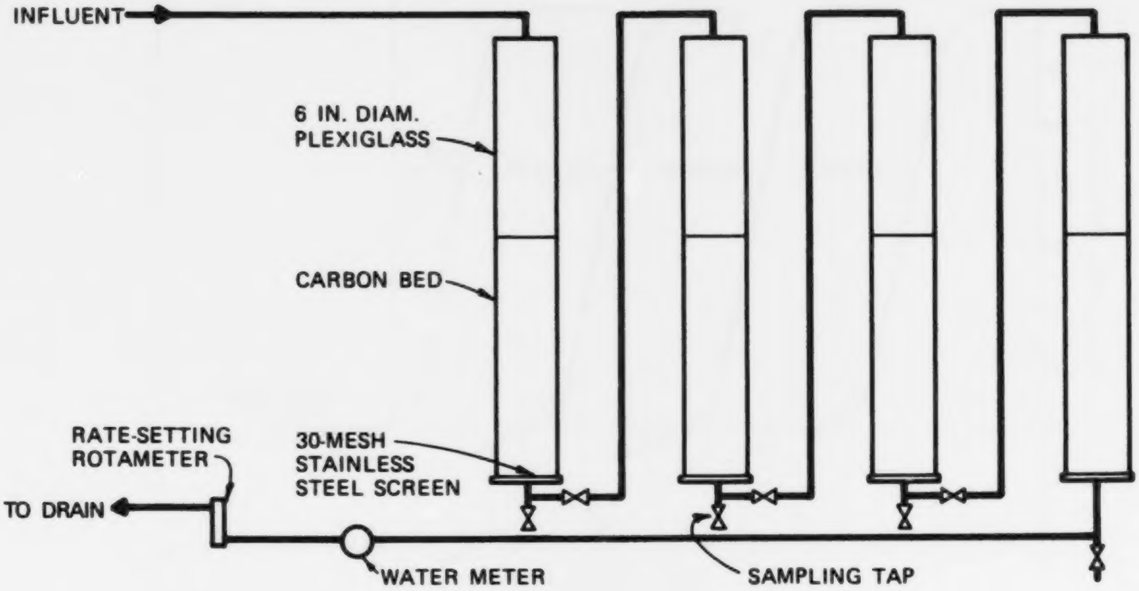

INFLUENT
6 IN. DIAM. PLEXIGLASS
CARBON BED
RATE-SETTING ROTAMETER
30-MESH STAINLESS STEEL SCREEN
TO DRAIN
WATER METER
SAMPLING TAP

FIGURE 4–5

DOWNFLOW PILOT CARBON COLUMNS

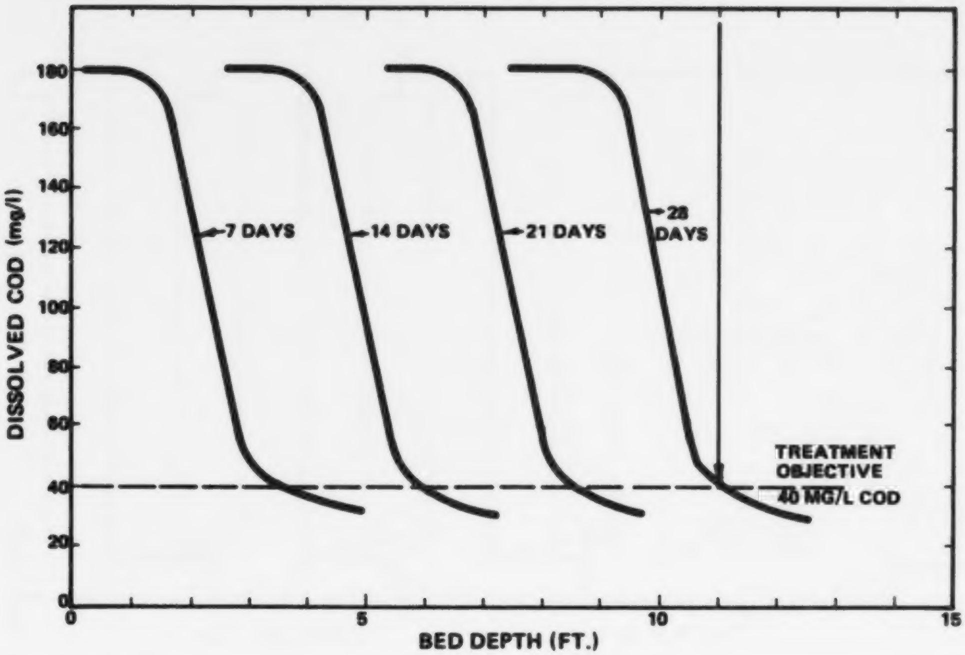


FIGURE 4–6

COD BREAKTHROUGH CURVES (IDEAL)

A broad wave front requires more carbon than a narrow wave front. However, the design safety factor required with a broad front is less than that with a narrow front. That is, when a breakthrough does occur, that amount of contaminant in the material coming through will be relatively stable in the broad front system, whereas with a narrow front after the breakthrough the concentration in contaminant will rise rapidly to equal that of the concentration in the influent.

In a narrow front system, it is important that provision be made for sampling at a point approximately 75 percent through the carbon train in order to monitor incipient breakthrough. This is in addition to the monitoring point that would exist at the end of the train.

This wave front factor will also affect the choice of systems in terms of using a fixed bed versus a moving bed. In the classic fixed bed system, the liquid is pumped down through the stationary bed until breakthrough occurs. This is satisfactory for broad front systems. On the other hand, for a narrow front it could be preferable to utilize a moving bed wherein the liquid is pumped upwards through the bed and periodically spent carbon is removed from the bottom for regeneration while fresh carbon is added at the top. This provides a large safety factor as there is always fresh carbon available in the system.

To illustrate the utility of pilot carbon column data, an example of pilot data and analysis follows. These data were collected from pilot columns of the type shown on Figure 4-4 at the South Tahoe Plant [1]. In this example, the purpose of the test was to compare four commercially available carbons. Four upflow pilot columns were charged with various types of carbon. Coagulated and filtered secondary effluent was pumped through the four columns in parallel. Samples were collected from each of the sample taps and analysed for COD at regular intervals. The resulting raw data are plotted on Figure 4-7 for one illustrative column. These raw data contain much useful information, but a mere plotting of COD vs. volume of water treated at various carbon depths yields a somewhat difficult-to-grasp picture unless further data analysis is made. One observation requiring no further analysis in this particular case was that one carbon (Brand C) was so friable that it was disintegrating and the column had to be shut down due to excessive headloss. Such an observation is of obvious utility if this brand of carbon were under active consideration for plant scale use.

The amount of COD removal per pound of carbon was calculated for each of the brands of carbon at various depths of carbon (as measured at the sample taps). The resulting curves are shown on Figures4-8 and 4-9 for two illustrative carbon depths.

In the lower bed depths, the Brand C carbon appears to have reached a saturation value of about 0.12 pound COD per pound of carbon. The other carbons did not appear to have reached a saturation value at the end of the run. At greater depths, the differences became more pronounced. After 0.25 pound COD per pound of carbon were applied, Brand D carbon had removed twice as much as the Brand B carbon and a third again as much as the Brand A carbon.

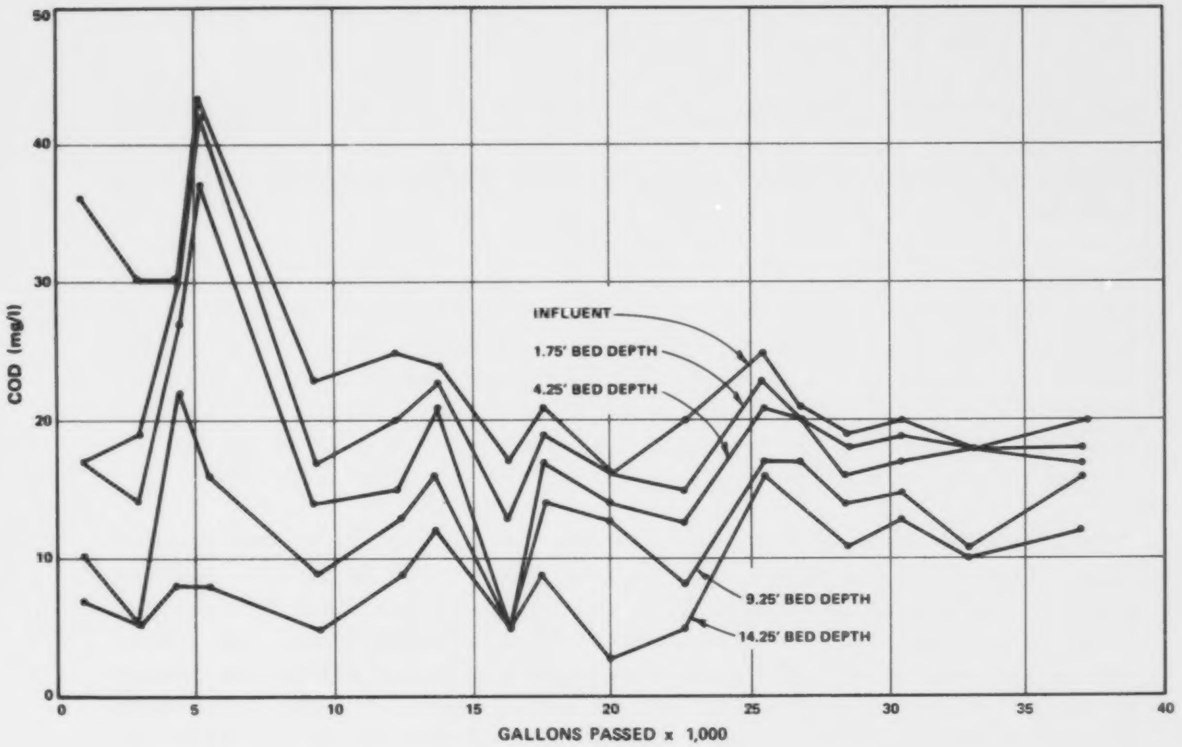


FIGURE 4–7

COD CONCENTRATION AT VARIOUS BED DEPTHS FOR UPFLOW PILOT COLUMN CHARGED WITH BRAND A CARBON

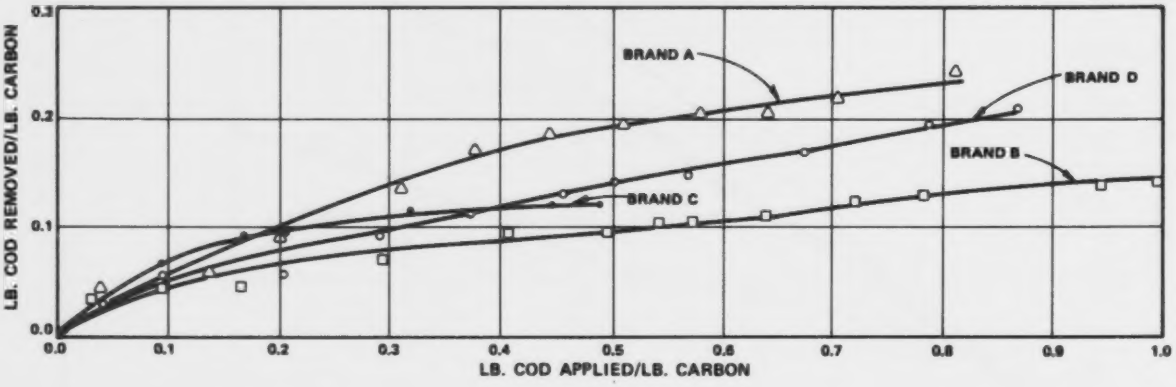


FIGURE 4–8

COMPARISON OF ADSORPTIVE CAPACITIES OF TEST CARBONS
4.25 FEET CARBON BED DEPTH – 4.6 MINUTE CONTACT TIME

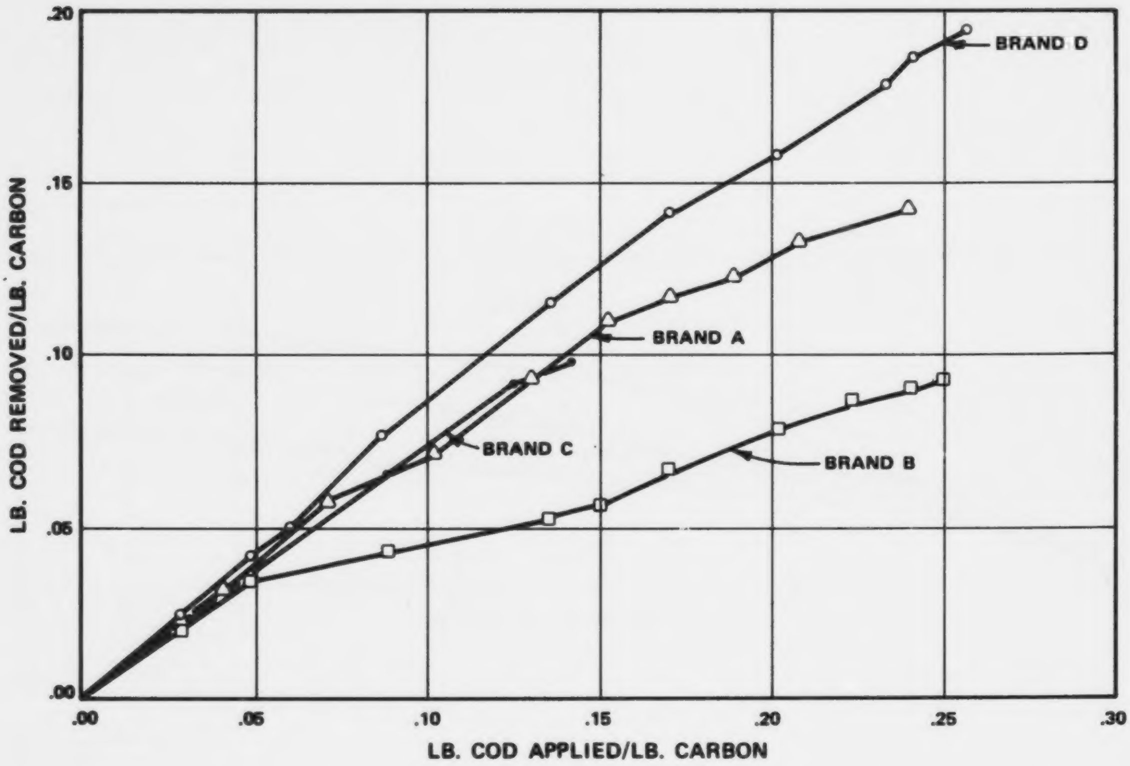


FIGURE 4–9

COMPARISON OF ADSORPTIVE CAPACITIES OF TEST CARBONS
14.25 FEET BED DEPTH – 17.5 MINUTE RESIDENCE TIME

Figure 4-10 shows the ratio of effluent COD concentration (C) to influent COD concentration (C_0) at three bed depths. From this graph, Brand D carbon can also be seen to be superior. By using the same data, the effects of contact time for the various brands of carbon were also compared as shown on Figure 4-11.The Brand D carbon, at a contact depth of only 9.25 feet, produced an effluent of the same quality as did the Brand A carbon after a 14.25 foot contact depth. At the end of the run, the Brand D carbon removed 56 percent of the influent COD at the 9.25-foot bed depth. During this period, 14.25 feet of the Brand A carbon averaged 57 percent COD removal.

The conclusions drawn from this pilot column comparison of the four carbons include:

1. The sample of Brand C, 12 x 40 mesh activated carbon, was shown to have the lowest saturation value (0.12 lbs removed/lb carbon) of the carbons tested.

2. The Brand C carbon also demonstrated a tendency for excessive headloss development. This problem may be related to the size and softness of the carbon.

3. The Brand B carbon sample tested was shown to exhibit a comparatively low rate of COD adsorption. Its saturation value was also below that of the Brand D and Brand A carbons.

4. The Brand D carbon proved superior to Brand A carbon, both in adsorptive rate and capacity. No saturation values were reached for these carbons during the study period, however.

This illustrative example shows the utility of pilot tests for comparing alternative carbons. They may also compare variables such as contactor configuration, varying degrees of pretreatment, etc., as discussed earlier.

4.6 Biological Activity and Carbon Adsorption

The extension of carbon capacity by biological action may be very significant under certain conditions. Weber [2] and several others have found that as activated carbon adsorbs organics from raw sewage it creates a highly enriched substrate for biological growth. This has two apparent treatment advantages: (1) extension of the carbon adsorption service life and (2) removal of non-adsorbable materials due to the biological activity. Weber [2] believes that the micro-organisms utilize the adsorbed organic matter (providing the organics are biodegradable) from the activated carbon surface, thus making the carbon available for continued use as an adsorbent. According to this concept, the carbon will trap organics for subsequent utilization by the micro-organisms. The limitation to biological regeneration is its inability to oxidize refractory (non-biodegradable) organics. Treatment advantages due to biological growth on the carbon may be offset by operational problems, as pointed out in Chapter 3.

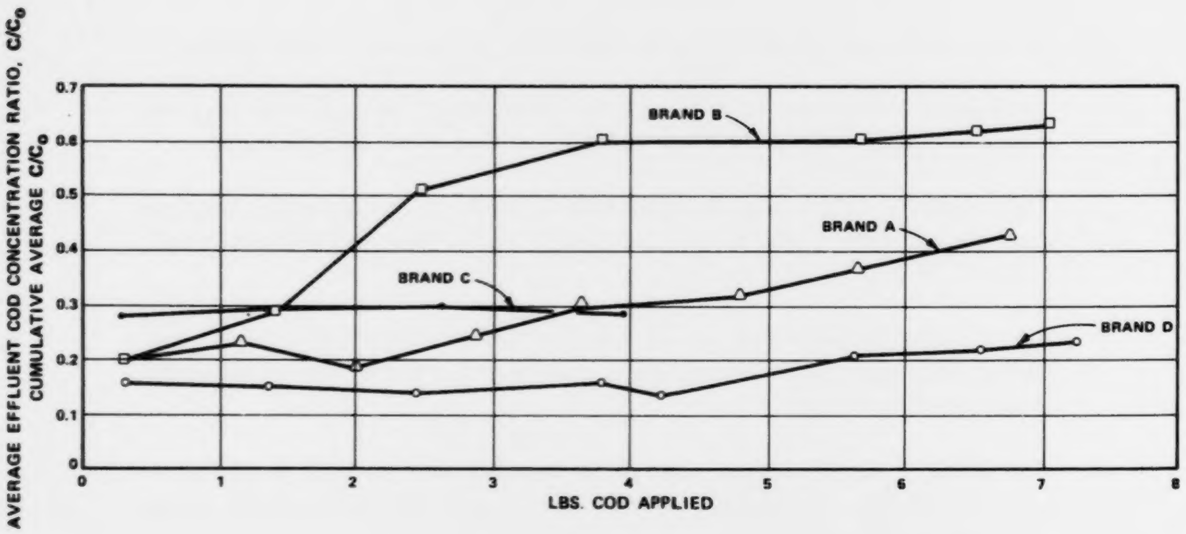


FIGURE 4–10

A COMPARISON OF THE COD REMOVAL ABILITY OF THE TEST CARBONS
SAMPLE DEPTH – 14.25 FEET

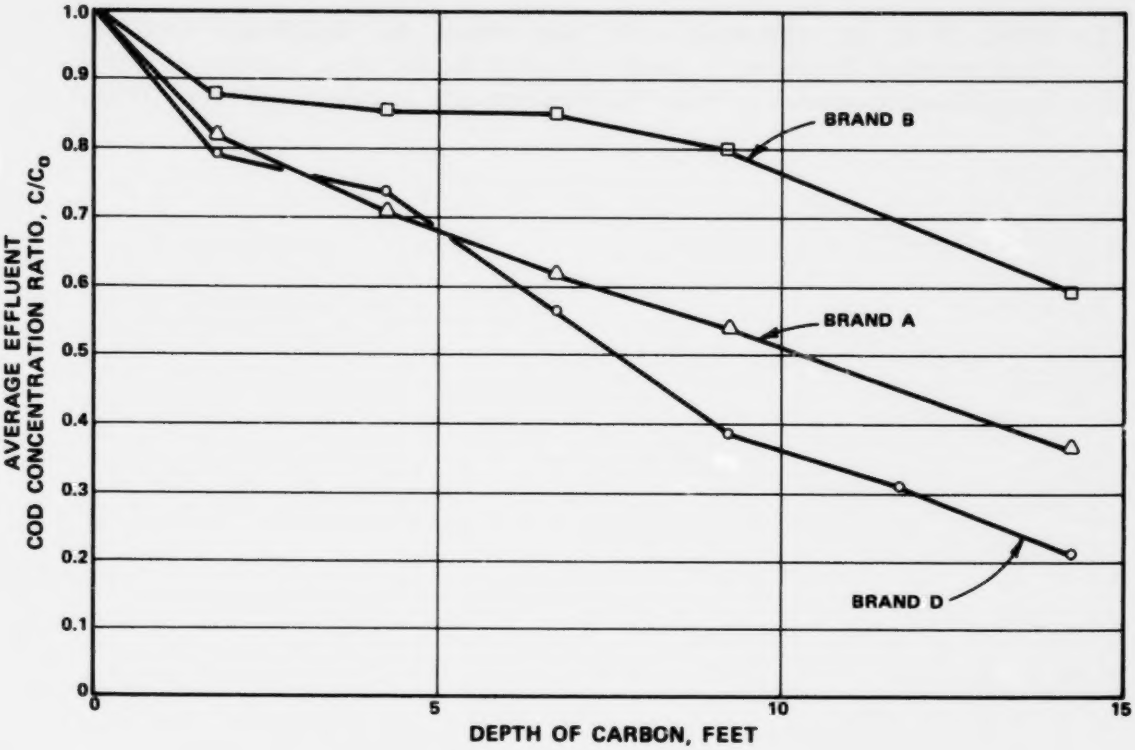


FIGURE 4–11

EFFECT OF CONTACT TIME ON COD REMOVAL
(APPROXIMATELY 0.2 LB. COD APPLIED PER LB. CARBON)

4.7 References

1. Smith, C. E., and Chapman, R. L., *Recovery of Coagulant, Nitrogen Removal, and Carbon Regeneration in Waste Water Reclamation,* EPA Report, Project WPD-85, June, 1967.

2. Weber, W. J., Jr., Friedman, L. D., and Bloom, R., *Biologically Extended Physicochemical Treatment.* A paper submitted for the Sixth Conference of the International Association on Water Pollution Research, Jerusalem, 18-24 June, 1972.

CHAPTER 5
CARBON ADSORPTION TREATMENT SYSTEM COSTS

5.1 Introduction

Presented in this chapter are data to allow estimation of capital, operation, and maintenance costs for the various components of activated carbon treatment systems.

Construction cost data are based insofar as possible on actual costs for plants existing or under construction, and detailed cost estimates for plants currently under design. In order to make the cost data current and comparable, the data has been adjusted by the use of the EPA Sewage Treatment Plant Cost Construction Index. The costs presented herein are based on a U. S. average cost index of 175.0 (valid approximately January, 1973).

Actual operation and maintenance costs experienced at the South Tahoe P. U. D. water reclamation plant are presented in detail as an example, and as a basis for cost estimates. All operation and maintenance costs are based on the condition of the plant operating at design levels; the cost per gallon of water treated (as opposed to annual costs) will increase under reduced plant operating load conditions.

The cost data are presented by a series of figures which are essentially based on either flow or carbon dosage. Approximate total costs for carbon treatment are presented on Figure 5-11 for various carbon dosages. More accurate, or adjusted carbon treatment costs can be developed through use of Table 5-7, a detailed cost estimating guideline.

The potential limitations of these cost estimates must be recognized. The cost curves are mainly graphical averages of numerous actual or estimated costs adjusted to a common time reference. Individual costs may vary significantly due to location, site conditions, associated treatment processes, economy of design, architectural features, union requirements, utility costs, the degree of competitive bidding, and numerous other factors. Also, actual cost data for construction, operation and maintenance are still quite limited, particularly in the case of large plants. Therefore, use of the cost data presented herein should be limited to initial process comparisons and selections, and preliminary cost estimates.

5.2 Capital Costs

5.2.1 Contactor Systems

Types of Contactors–numerous types of carbon contactor systems have and will be developed, including:

1. Upflow packed beds.

2. Upflow expanded beds

3. Downflow packed beds in gravity and pressure units.

   a. series

   b. parallel

4. Various combinations of the above.

The operating characteristics and design examples of these systems have been discussed in detail in Chapter 3. There is little cost difference between upflow packed and expanded beds; the "packed" bed contactor is, in fact, usually sized so as to allow periodic expansion of the bed for washing purposes.

Downflow series operated packed beds can be expected to be more expensive than upflow parallel columns, while downflow parallel packed beds will be about the same cost as upflow contactors. Both the upflow and downflow contactors would have an equal contact time and volume; upflow contactors require a screening system at the top while a downflow contactor, with additional free board, may allow the use of a less expensive perforated header system. The downflow type contactor, however, will require a more elaborate underdrain and will also require surface wash equipment. Therefore, downflow and upflow contactors should be nearly equal in cost.

Next, consider the series downflow mode of operation, and evaluate the use of a single upflow contactor of volume (V) compared to a two-stage series downflow contactor system, each contactor having a volume of $\frac{V}{2}$. Again, each system offers an equal contact time. An economy of scale analysis can be utilized to estimate relative costs. The cost exponent (M) for similar pressure vessels has proven to be about 0.65 [1].

The relative costs can be computed as follows [1]:

$$C_{2\text{-stage}} = C_{1\text{-stage}} \frac{V}{2}^{0.65} \times (2)$$

If $C_{1\text{-stage}}$ and V are set at unity:

$$C_{2\text{-stage}} = (1/2)^{0.65} \times (2)$$

$$C_{2\text{-stage}} = 1.28$$

where:

$C_{1\text{-stage}}$ = Cost of single contactor of volume V

$C_{2\text{-stage}}$ = Cost of 2 series contactors, each of volume $\frac{V}{2}$

By this analysis, the 2-stage series downflow units would cost approximately 28 percent more than single stage contactors. Table 5-1 presents a summary of relative costs of various contactor systems available.

TABLE 5-1
RELATIVE COSTS OF VARIOUS CONTACTOR SYSTEMS

System	Cost Adjustment Factor
Upflow countercurrent packed bed	1.0
Upflow countercurrent expanded bed	1.0
Downflow-parallel	1.0
Downflow-series	1.28

Materials of Construction–materials of construction will also influence contactor system costs to some extent. For small contactors up to 12-foot diameter, shop-fabricated steel vessels with coal tar epoxy internal coating prove most economical. Beyond 12-foot diameter, field fabrication is usually necessary. Under this condition, concrete construction is competitive, and offers reduced maintenance costs.

Actually, basic contactor costs represent only on the order of 25 percent of the cost of the total contactor system including screens, piping, valves, instrumentation, building, and so forth. Therefore, for large contactors, the choice of steel versus concrete should be based on such factors as type of contactor, exposure, foundation conditions, local contractor capabilities, salvage value, corrosion potential, etc. As will be illustrated hereinafter, the materials of construction appear to have minimal impact on the total construction cost of the contactor system.

Cost Estimates–cost estimating curves for carbon contactors are presented on Figures 5-1 and 5-2. On Figure 5-1, the costs are indicated relative to the effective volume per contactor. As noted, these costs are not for the contractor only, but include total system

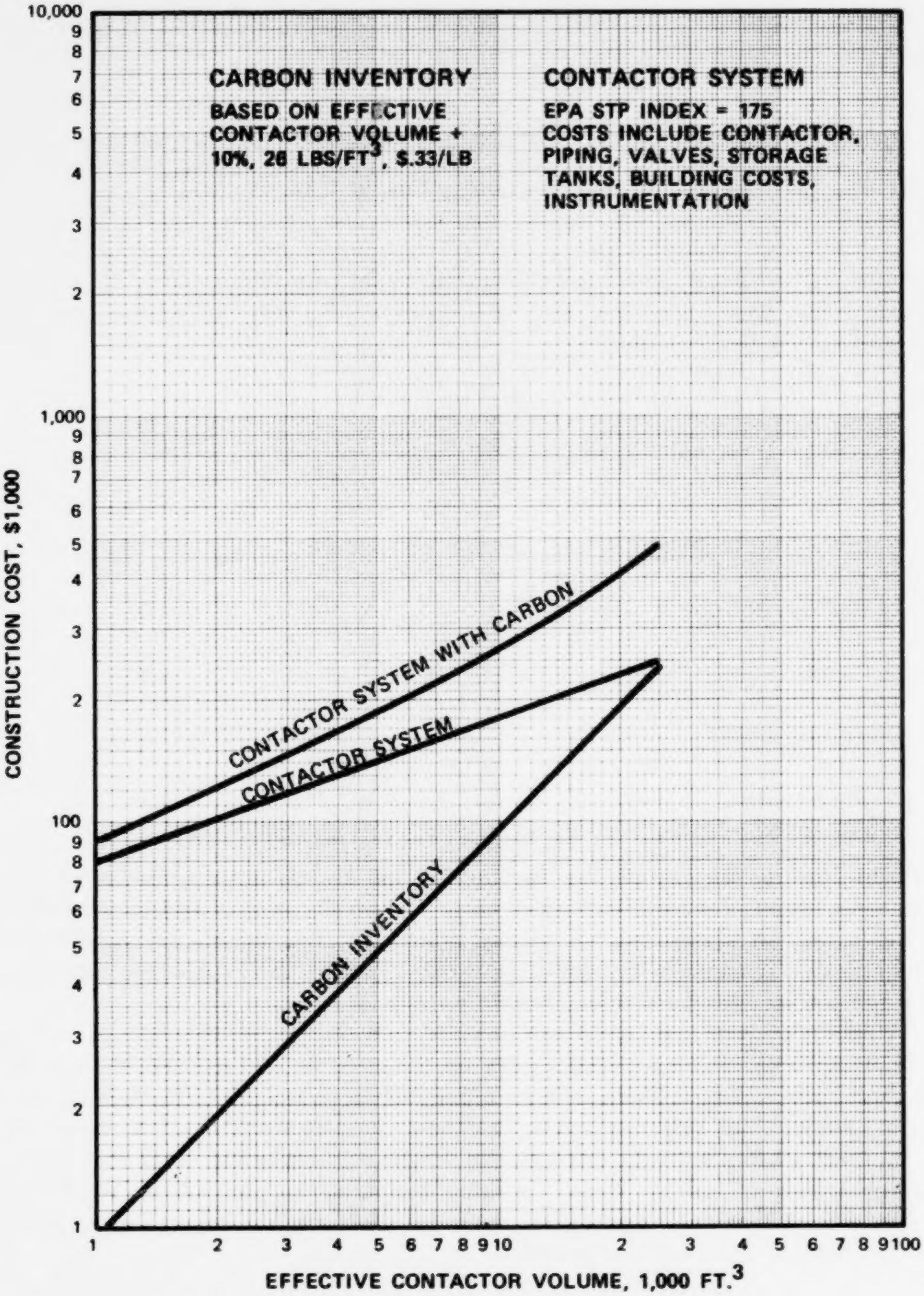


FIGURE 5–1

CONTACTOR SYSTEM COSTS BASED ON CONTACTOR SIZE

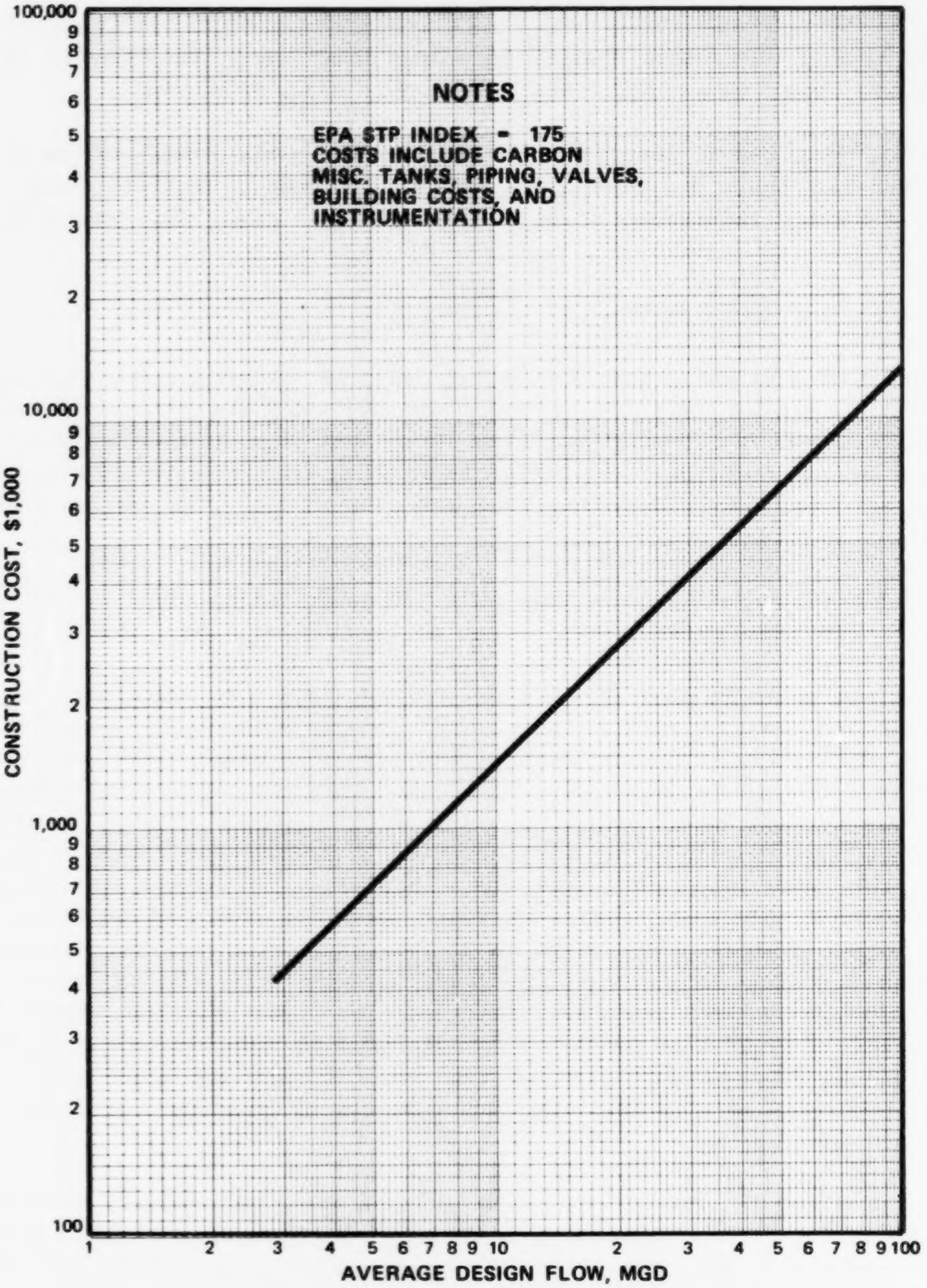


FIGURE 5–2

CONTACTOR SYSTEM COSTS BASED ON DESIGN FLOW AND 30 MINUTES CONTACT costs, including a 10 percent allowance for makeup carbon storage. On Figure 5-2, the costs are presented relative to plant flow with a contact time of 30 minutes.

The data points used in developing Figure 5-2 include a variety of contactor systems, including both upflow and downflow of both steel and concrete construction. Again, type of contactor and materials of construction do not dramatically affect total system cost.

5.2.2 Regeneration Systems

Carbon regeneration cost estimates have been divided into basic furnace system costs, and complete regeneration system costs, as presented on Figure 5-3. The costs are referenced to furnace hearth area. Required hearth area can be easily calculated from the required pounds per day regeneration rate, and the design hearth loading, which is usually 40 lbs/sq ft/day (see Chapter 3). As indicated, complete regeneration system costs add about 50 percent to the basic installed furnace costs.

5.2.3 Wastewater Treatment Plant Size for Economic Regeneration of Granular Carbon

The purpose of this discussion is to determine the approximate plant capacity for various types of AWT plants for which it is economical to provide on-site facilities for granular carbon regeneration. At best, the figures derived will be for rough rule-of-thumb use. Obviously, there will be enough differences in prevailing local conditions and available alternates to require individual project consideration and analysis. For example, in some metropolitan areas carbon regeneration facilities may be available on a commercial basis, at a jointly owned and operated central regeneration plant, or by contract with a larger sewer authority. The cost of loading and hauling spent and regenerated carbon would have a great influence on the desirability of these alternates as compared to on-site facilities. In addition, the use of powdered carbon on a throwaway basis may present a good alternate for small plants in a few cases. The present discussion includes a comparison of the costs of granular carbon regeneration at small plant scale versus the costs of using granular activated carbon on a throwaway basis. The cost of disposal of the spent granular carbon is so small compared to the cost of the carbon that it can be ignored for this purpose.

The cost of granular activated carbon delivered to the plant site is taken at $0.33 per pound which is probably typical for the continental United States at the present time. In other locations (in Alaska, for example) the cost of granular carbon may be $0.40 per pound or more.

Estimates of costs for regeneration of granular carbon can be made rather accurately for small scale plants due to the fact that the regeneration must be done using the smallest

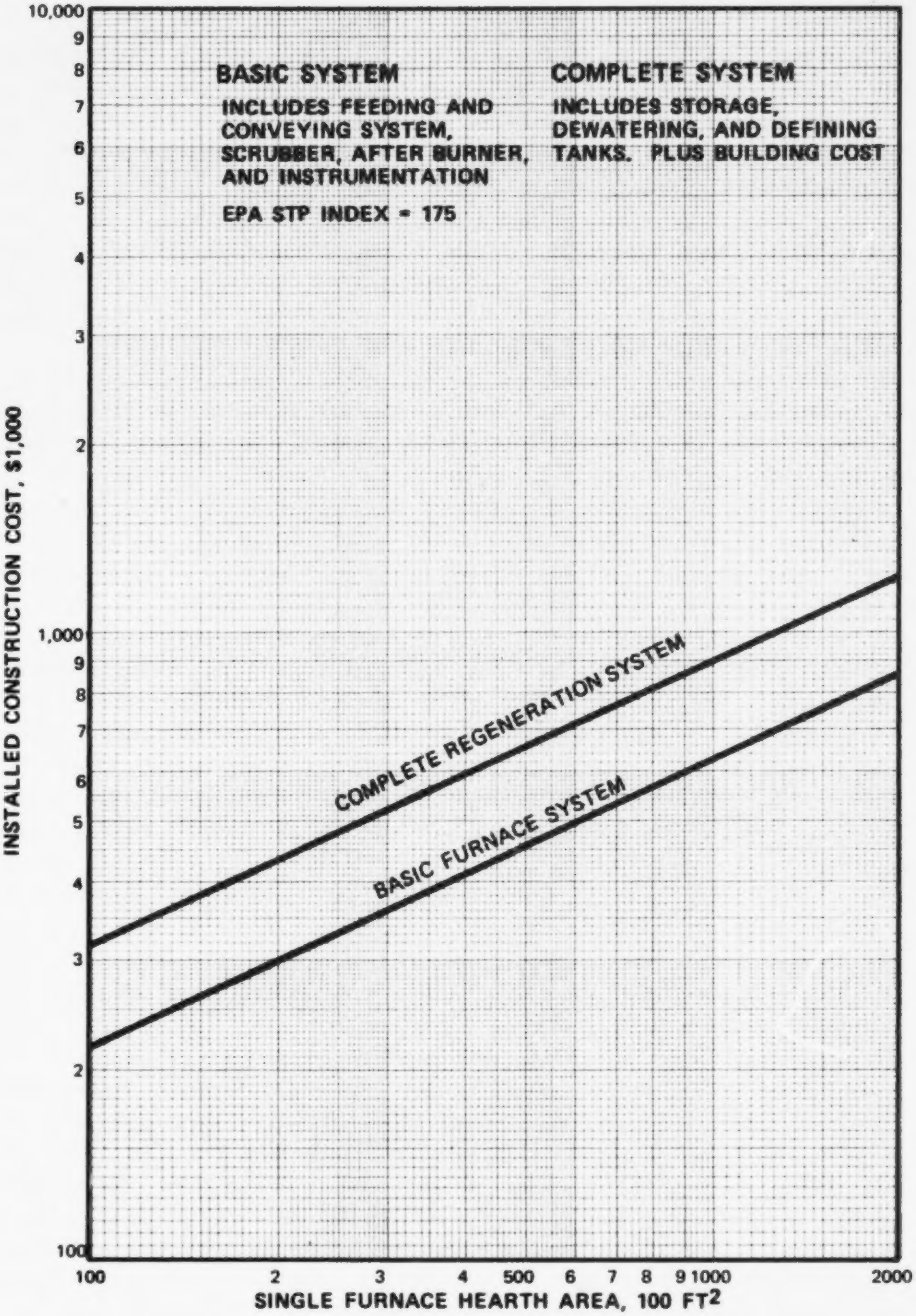


FIGURE 5–3

CARBON REGENERATION SYSTEM CONSTRUCTION COST commercially available fully automated furnace (54-inch I. D.). (A 30-inch I. D. furnace is available as a commercial, skid mounted unit, but is not automated to the degree that the 54-inch I. D. furnace is.) The 54-inch furnace has been in use for seven years at the South Tahoe water reclamation plant and complete detailed cost records are available for installation and operation of this system.

The rated capacity of this furnace when it was first installed was 6,000 lbs/day, or about 63 lbs/sq ft/day. However, EPA demonstration grant studies completed in 1971 showed that the actual furnace capacity was very close to 3,800 lbs/day or 40/lbs/sq ft/day. Table 6-8 illustrates the actual data collected at Tahoe.

Using the current data, the 54-inch I. D. carbon regeneration furnace at Tahoe has a maximum rated capacity of 3,800 lbs/day. Granular carbon dosages for different plants may range from 200 to 1,800 pounds per million gallons depending upon the character of the wastewater, effluent requirements, the AWT processes used and the pretreatment provided. Allowing 20 percent downtime, a 3,800 lbs/day maximum capacity furnace would have a firm capacity of 3,000 lbs/day and might serve plants having rated capacities up to 15 mgd depending upon their carbon dosage requirements.

Figure 5-4 gives the cost in cents per pound to regenerate carbon in a 54-inch gas-fired multiple hearth unit at various furnace throughput rates up to 3,000 lbs/day as derived from the Tahoe data. From this curve, it is seen that when plant carbon regeneration requirements are less than 190 lbs/day, the cost of regenerated carbon equals the cost for granular carbon used on a throwaway basis. Further, the curve shows that carbon regeneration costs increase quite sharply for furnace throughputs less than 1,500 lbs/day. For intermediate needs ranging from 3,000 down to 1,500 lbs/day of carbon, the carbon regeneration costs only rise from $0.09 to $0.11 per pound, but from 1,500 down to 190 lbs/day they increase from $0.11 to $0.30 per pound of carbon.

So far as provision for on-site carbon regeneration is concerned, small plants can be placed into three categories according to their carbon usage:

1. For plants with carbon usage less than 200 lbs/day, carbon regeneration facilities should not be provided. If granular carbon is to be used, it would be on a once-through throwaway basis, or the spent carbon would be transported to and from a central regeneration station if one is available. This category would include AWT plants using the tertiary sequence of treatment having a carbon usage of about 250 pounds per million gallons (lbs/mg) and smaller than 800,000 gpd capacity, and PCT plants having a carbon usage of about 1,200 lbs/mg and smaller than 170,000 gpd capacity.

2. When average carbon regeneration requirements exceed 1,500 lbs/day, there is no question but that on-site carbon regeneration facilities should be built. This

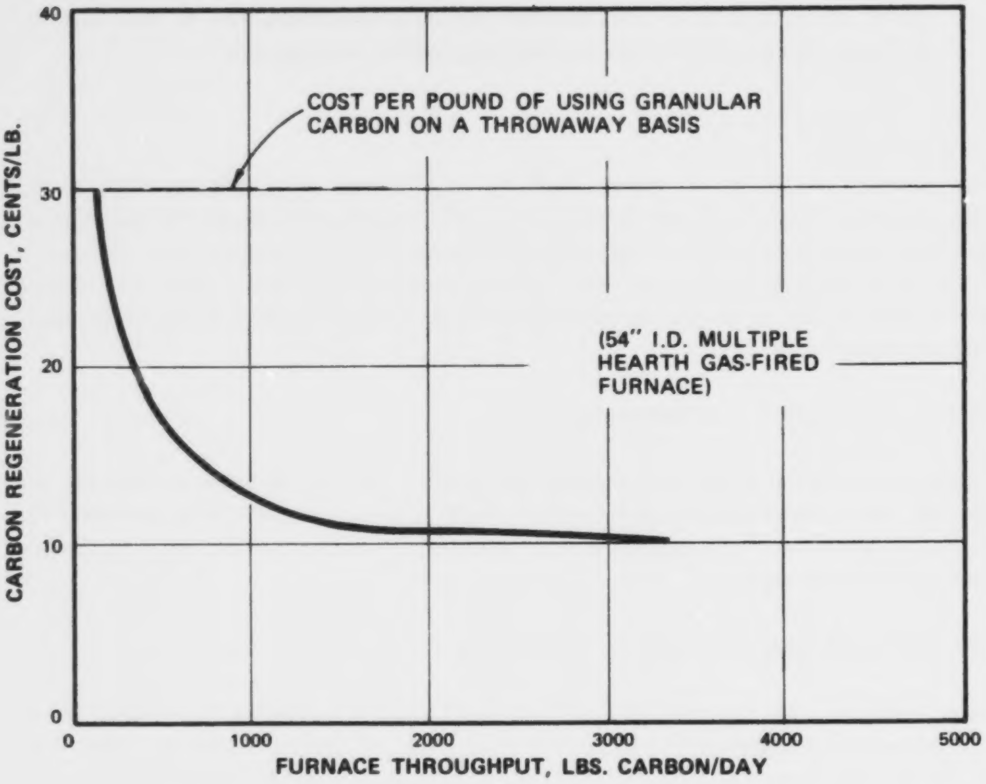


FIGURE 5–4

CARBON REGENERATION COST VS. THROUGHPUT

category would include tertiary plants having capacities greater than 6 mgd and physical-chemical plants rated at 800,000 gpd or more.

3. For carbon usages between 200 and 1,500 lbs/day, which would include tertiary plants with capacities between 0.80 and 6.0 mgd and PCT plants with capacities between 170,000 and 800,000 gpd, the cost of on-site regeneration must be compared to the costs of central regeneration and to the costs of alternate treatment methods for removing refractory organics.

5.2.4 Influent Pump Stations

In most installations, a pump station will be required to force effluent through the contactor system. Figure 5-5 can be used to obtain approximate costs for this type of intermediate pump station. The costs are, of course, only approximate since the actual costs will vary with location and total dynamic head requirements. Note also that a common pump station is frequently used for series operation of filters ahead of, or after, the carbon contactors.

5.2.5 Total Capital Cost Adjustment

To obtain total capital costs, the construction costs must be adjusted to account for engineering, legal, administrative, land, and interest expenses. Figure 5-6 is provided for this purpose. As shown, these items can add 20 to 25 percent to the construction cost of a carbon treatment system.

5.3 Operation and Maintenance Costs–Tahoe Data

Extensive operation and maintenance cost analyses were developed at the South Tahoe P. U. D. water reclamation plant based on actual expenses during 1969 and 1970. The results are presented herein to illustrate relative costs and to serve as a basis for extension of these data to current conditions and alternate capacity plants. The unit costs in effect at Tahoe during the analysis period are summarized in Table 5-2. Resultant operation and maintenance costs, and relative capital costs, for activated carbon treatment are shown in Tables 5-3, 5-4, and 5-5. At Tahoe, activated carbon adsorption follows primary and secondary treatment, chemical treatment and mixed-media filtration. The activated carbon system includes eight steel columns, each containing 22-25 tons of 8 x 30 mesh granular activated carbon. The filter effluent flows upward under pressure through the columns.

Operational labor includes flow monitoring, sampling, and backwashing of columns. Maintenance includes instrument calibration, corrosion inspection of the interior of the columns, and repair of appurtenances. Fifty percent of the pumping costs, including maintenance for pumping through filters and carbon columns was assigned to the carbon adsorption system. The initial carbon charge for the carbon column was included in the capital cost.

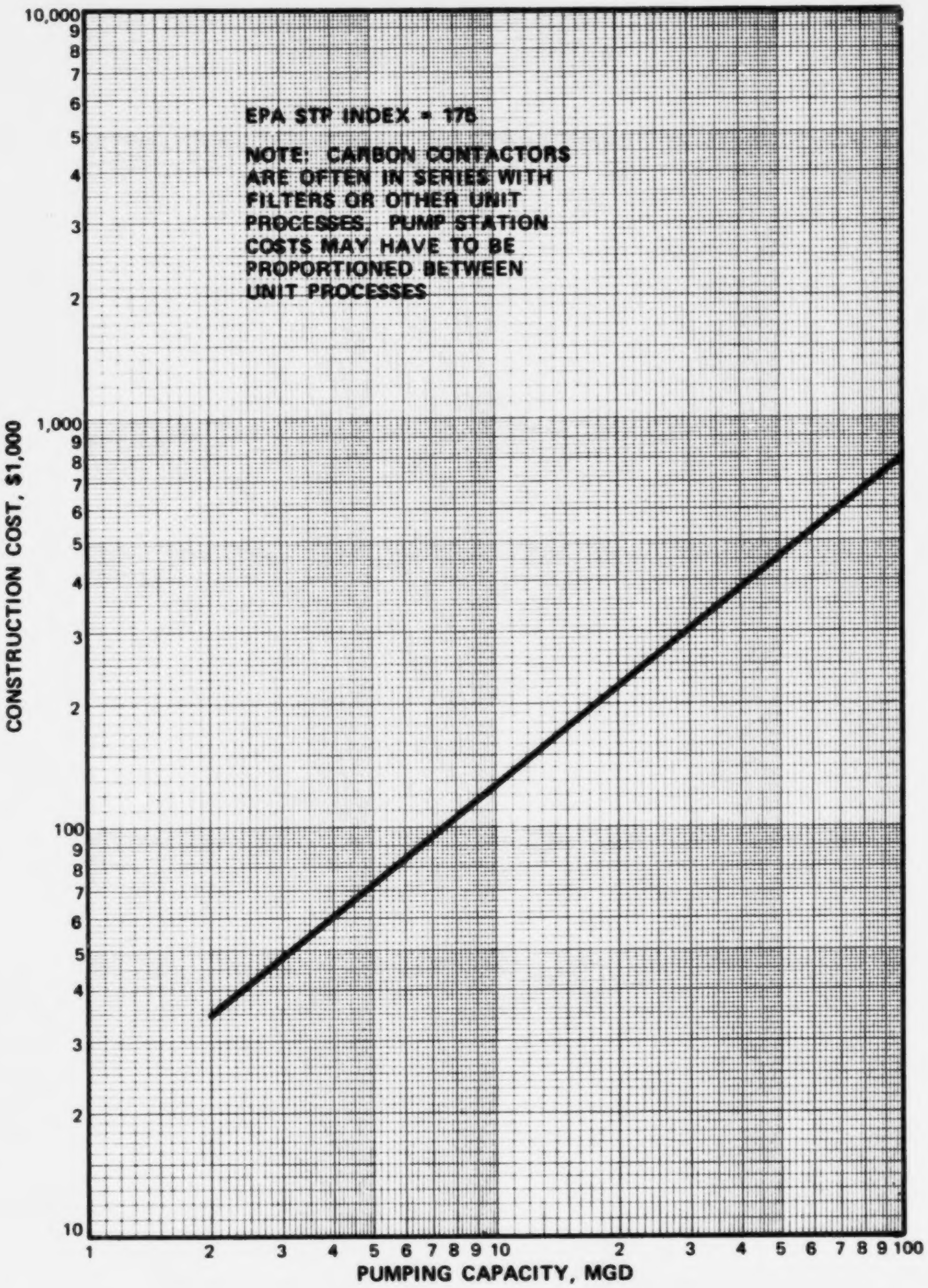


FIGURE 5–5

CARBON ADSORPTION PUMP STATION COST

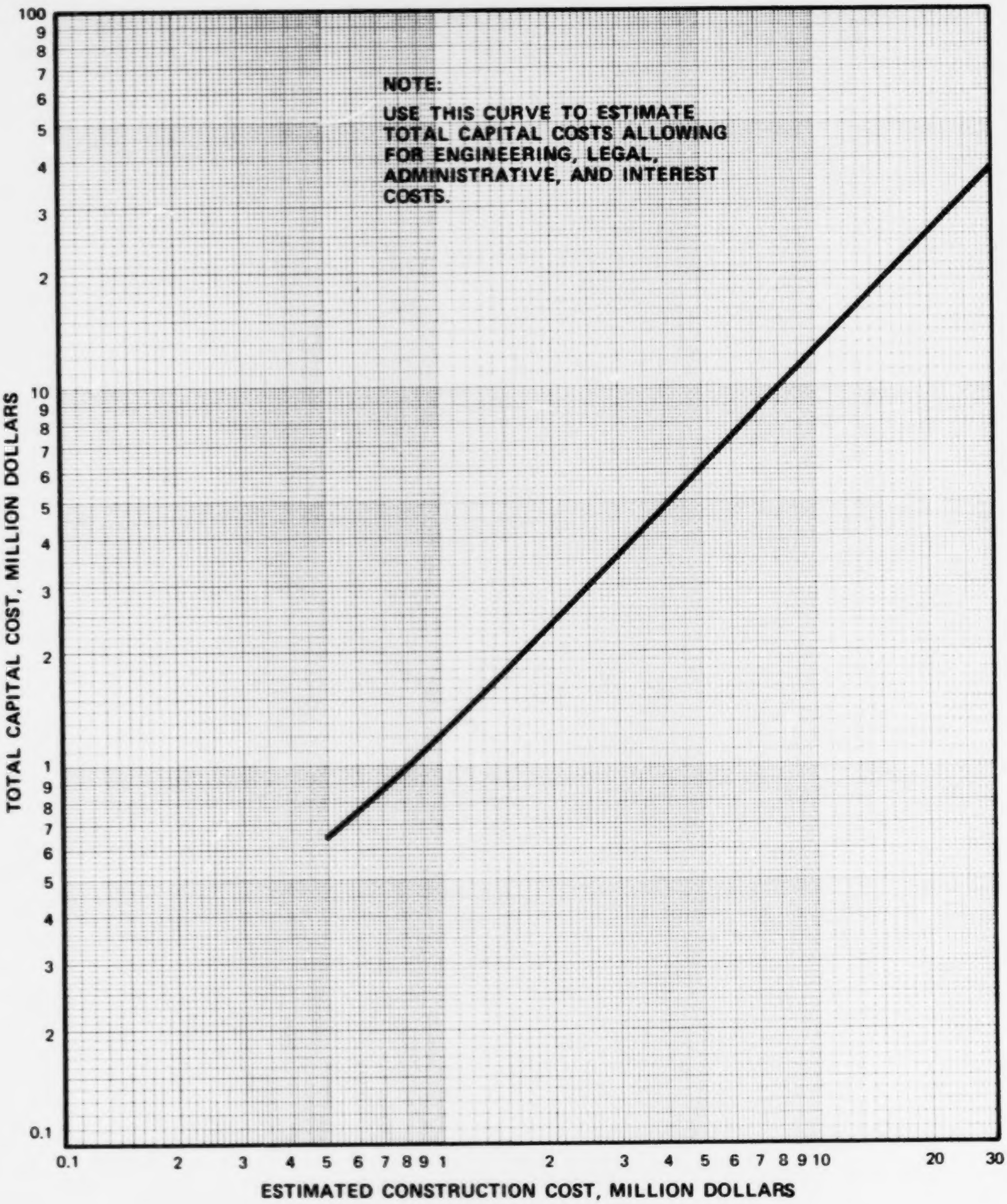


FIGURE 5–6

TOTAL CAPITAL COST DEVELOPMENT

Spent carbon is regenerated at 1,650 degrees to 1,750 degrees F in a multiple hearth furnace. The furnace can be operated at feed rates of 100 to 6,000 lbs/day. After regeneration, the activated carbon is returned to the columns. Carbon losses used for the cost analysis averaged 8.9 percent.

TABLE 5-2

UNIT COSTS AT SOUTH LAKE TAHOE (1)

Labor (2)	
Operations	\$ 6.11/hour
Maintenance	\$ 5.05/hour
Electricity(3)	\$12.10/1,000 kwh
Fuel (4)	\$ 0.0543/therm
Activated Carbon Makeup	\$ 0.305/pound

(1) All appropriate unit costs are for years 1969 and 1970 and are fob South Lake Tahoe and include a 5 percent California sales tax.

(2) Labor costs include all direct and indirect monies paid upon the employees behalf. The rates are averages for 1969 and 1970.

(3) Includes energy and demand charges.

(4) Natural gas at about 860 BTU/cu ft at 6,200 feet elevation and billed on the basis of interruptible service.

TABLE 5-3
CARBON ADSORPTION OPERATING AND CAPITAL COSTS AT SOUTH LAKE TAHOE
1969-1970

Operating Costs	$/Day
Electricity	47.34
Operating Labor	24.53
Maintenance Labor	3.27
Repair Material	1.15
Instrument Maintenance	4.24
Total Operating Cost	80.53

Total Cost	$/Million Gallons
Operating (1)	10.74
Capital (2)	16.30
Total	27.04

(1) Total operating cost shown is based on a flow of 7.5 mgd. Total operating cost per MG of water treated, including the 7.5 mgd plant influent plus recycle streams, would be $8.77/MG.

(2) Includes initial carbon charge. All capital costs were adjusted to EPA, STP Index 127.0, amortized at 5 percent for 25 years.

TABLE 5-4
CARBON REGENERATION OPERATING AND CAPITAL COSTS AT SOUTH LAKE TAHOE
1969-1970

Operating Cost	$/Day
Electricity	2.23
Natural Gas	6.15
Makeup Carbon	70.39
Operating Labor	91.90
Maintenance Labor	16.21
Repair Material	1.17
Instrument Maintenance	1.90
Total Operating Cost	189.95

Total Cost	$/Million Gallons
Operating (1)	25.33
Capital (2)	5.20
Total	30.53

(1) Total operating cost shown is based on a flow of 7.5 mgd. Total operating cost per MG of water treated would be $19.28/MG including 7.5 mgd plant influent, plus recycle flows. Contactors are designed for 8.2 mgd.

(2) Capital costs were adjusted to EPA, STP Index 127.0 and amortized at 5 percent for 25 years.

TABLE 5-5
CARBON REGENERATION OPERATING AND CAPITAL COST PER TON OF CARBON REGENERATED AT SOUTH LAKE TAHOE 1969-1970

Operating Cost	$/Ton
Electricity	1.73
Natural Gas	4.72
Makeup Carbon	53.98
Operating Labor	68.74
Maintenance Labor	39.52
Repair Material	2.36
Instrument Maintenance	1.43
Total Operating Cost	172.48

Total Cost	$/Ton
Operating	172.48
Capital	29.76
Total	202.24

Electricity included power used for instrumentation, driving rabble arms, and fans for shaft cooling, induced draft, and combustion air. Natural gas and makeup carbon are self-explanatory. Operational labor included furnace operation, de-fining, transferring spent and regenerated carbon, and regeneration efficiency analysis. Maintenance labor and repair material were for the furnace, instrumentation, and carbon transfer appurtenances. Maintenance costs for 1969 and 1970 included furnace startup and shutdown every 4 to 8 weeks, cleaning carbon dewatering and de-fining screens, carbon slurry pumps and stack-gas scrubber. The extensive maintenance of furnace startup and shutdown would be eliminated if regeneration were continuous.

5.4 Personnel Requirements

Personnel or labor requirements for varying-sized carbon treatment systems have been separated in terms of operation, maintenance, and laboratory efforts. Estimated annual man-hour requirements for each category are presented on Figures 5-7 and 5-8.

Operational labor for carbon adsorption includes flow monitoring and control, sampling, and contactor backflushing. Maintenance in this area includes instrument calibration, pump station upkeep and repairs, inspection, and repair of appurtenances.

Operational labor for carbon regeneration includes carbon transfer, furnace operation including simple control analyses, and carbon defining. Maintenance labor includes instrument calibration, furnace upkeep and repairs, transfer and de-fining equipment repair, and cleanup.

Laboratory labor costs allow for performance of routine control analyses on carbon contactor influent and effluent (COD or TOC, color, MBAS), plus analyses of composite samples of spent and regenerated carbon quality (apparent density, Iodine Number, occasional sieve analyses, etc.). No allowance is made for additional analyses as might be performed for final effluent quality reporting, or for research purposes.

All personnel estimates include a 5 percent allowance for supervision and administrative costs. The man-hour requirements were developed from actual experience at Tahoe, and include the effect of labor efficiency. No adjustment is necessary to include an allowance for "productive" man-hours.

5.5 Operation and Maintenance Costs

Annual operation and maintenance cost estimates are presented graphically on Figures 5-9 and 5-10. All costs are based on the assumption that the plant is operating at the design rate. The various components of total annual costs were included so that they may be individually adjusted to suit local conditions. The assumed unit costs are summarized in Table 5-6.

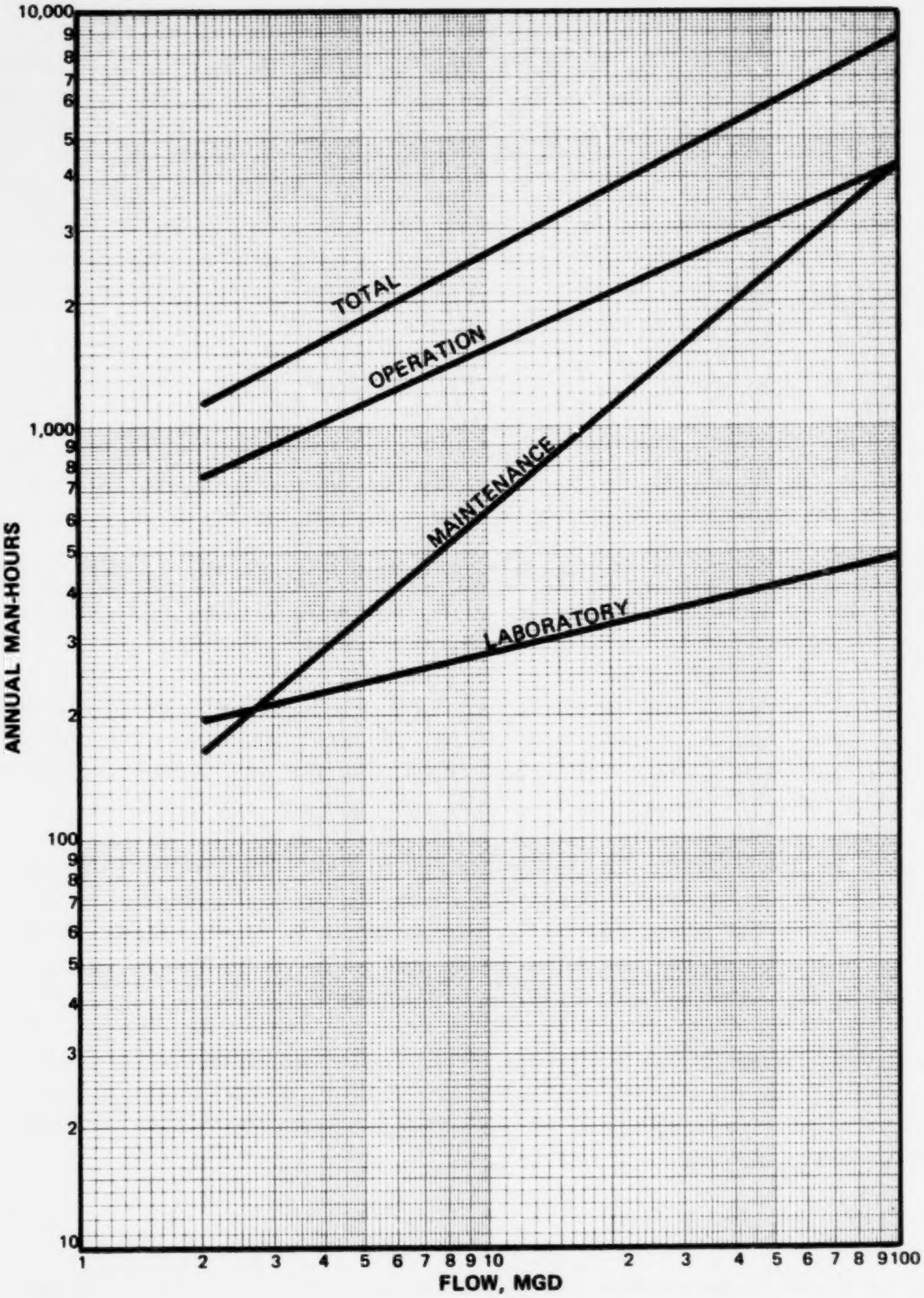


FIGURE 5–7

CARBON ADSORPTION LABOR REQUIREMENTS

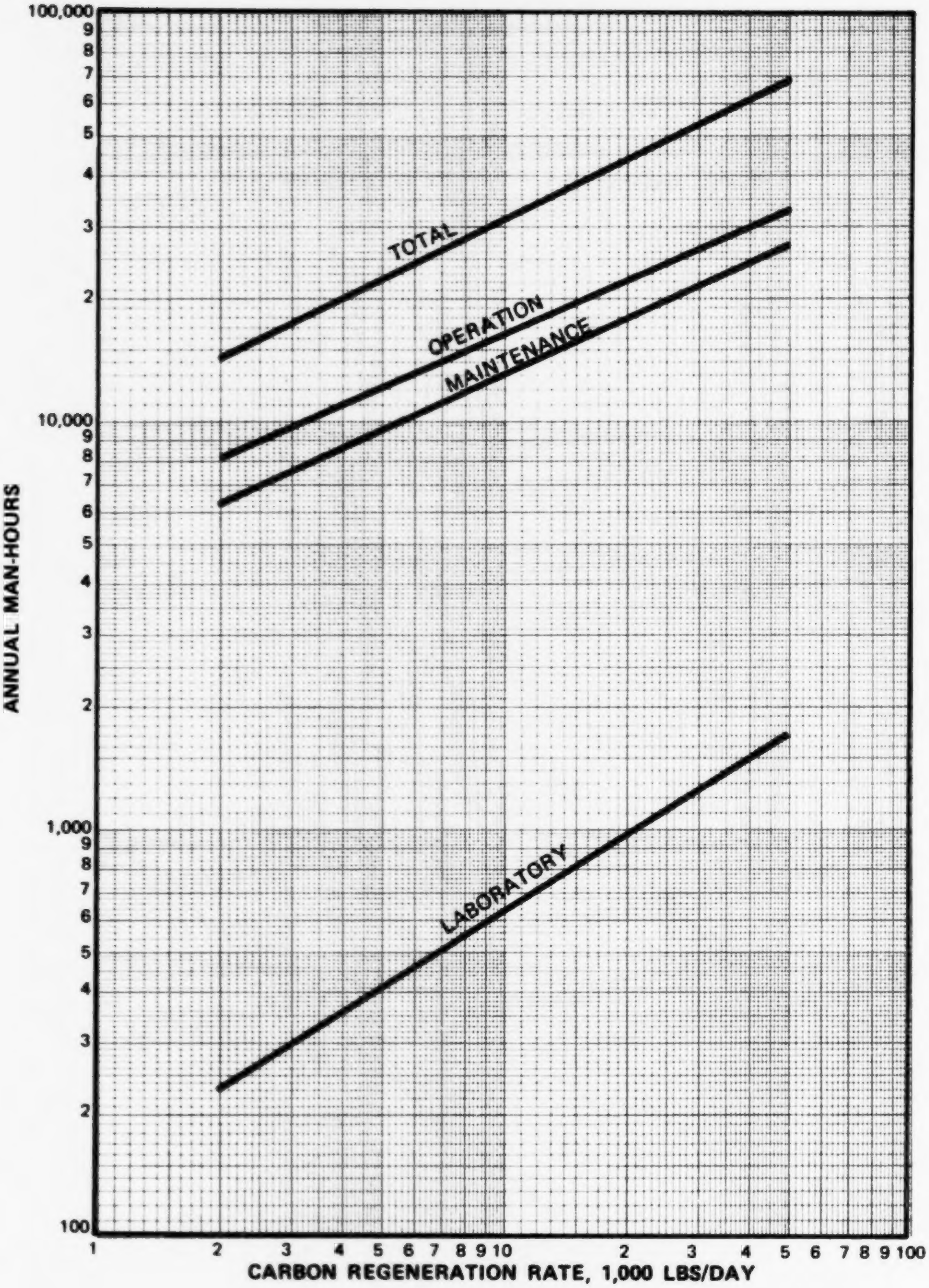


FIGURE 5–8

CARBON REGENERATION LABOR REQUIREMENTS

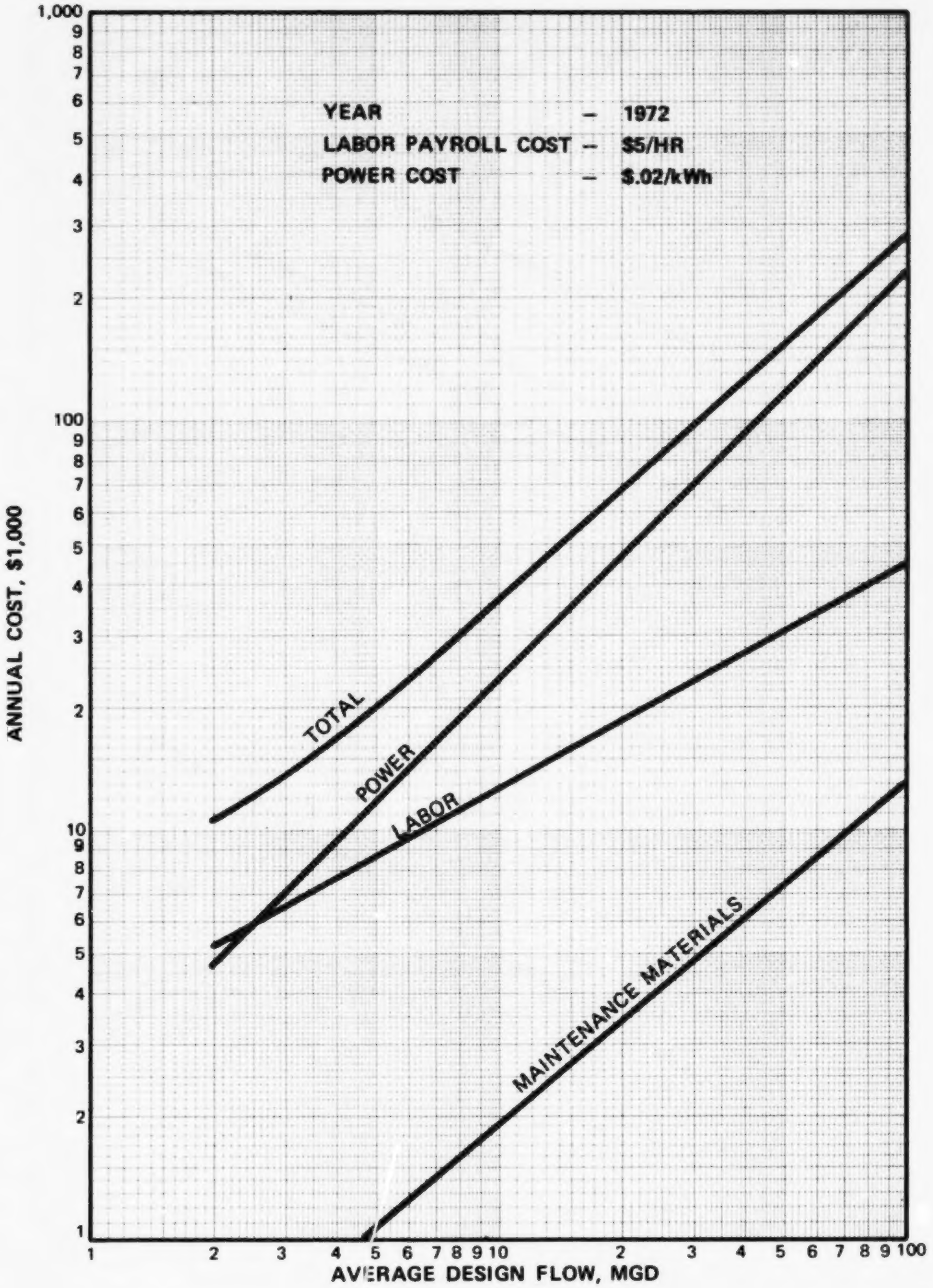


FIGURE 5–9

CARBON ADSORPTION
OPERATION AND MAINTENANCE COSTS

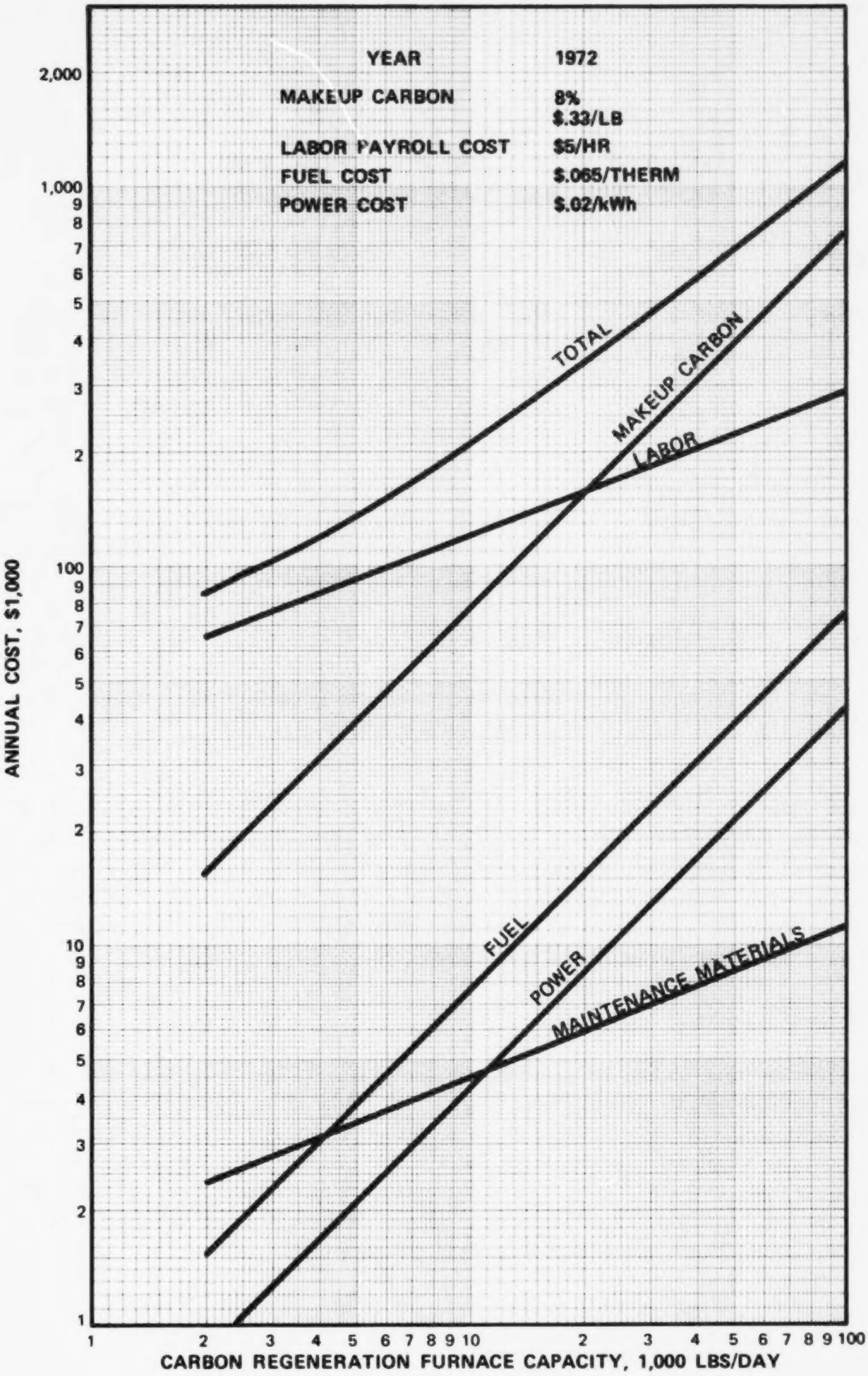


FIGURE 5–10

CARBON REGENERATION
OPERATION AND MAINTENANCE COSTS

TABLE 5-6
SELECTED UNIT COSTS FOR ESTIMATING OPERATION AND MAINTENANCE COSTS

Item	Value	Basis for Selection
Labor	\$5/hr	U. S. Department of Labor, Bureau of Labor Statistics SIC Code 494-7 "Water, Steam and Sanitary System" classification, Sept. 1972. Listed value–\$4.00/hr. Increased by 25 percent to adjust to actual payroll costs.
Power	\$0.02/kwh	Estimated national average power cost including demand and energy charges w/o consideration of other plant power demands.
Fuel	\$0.065/therm	Northwest Natural Gas Company Firm Service-High Load Factor rate schedule. Used average of \$0.06 to \$0.07/therm depending on demand. Rates are about average for the nation.

Again, the operation and maintenance cost are estimates primarily referenced to actual experience at Tahoe. The estimates should be quite close for similar plants through approximately 20 mgd. The accuracy may diminish for substantially larger plants, or plants using considerably different contactor systems. This variance would be particularly true in the case of adsorption system power requirements; shallow, non-pressurized contactors would require substantially less power.

5.6 Effects of Recycle Flows on Costs

Potential recycle flows should be evaluated for each plant. Often times, final effluent is used for internal plant non-potable water uses. Depending upon the pre- and post-treatment sequence, recycle flows of up to 20 to 35 percent of plant influent flow can occur. Typical uses include backwash water, scrubber water, chemical dilution water, cooling water, and so forth. This recycle must of course be provided for, and thus will increase the capital cost of the adsorption system. Pumping power will be the only significant resultant increase in operation and maintenance cost.

5.7 Cost Estimating Guides

Table 5-7 has been included for use as a guideline in using the cost curves presented herein to develop preliminary cost estimates. Thus, the capital, operation and maintenance and total annual costs can be estimated for any combination of flow and estimated carbon dosage. Table 5-7A contains a completed example. Note that adjustments can be made for alternate unit costs.

Figures 5-11 and 5-12 are included for carbon treatment estimating. These figures can be utilized if the assumptions and unit cost bases of the various components are acceptable.

5.8 Summary of Carbon Treatment Costs

Table 5-8 contains a distribution of estimated costs for the examples developed in Table 5-7A. The total annual cost comparison shows that carbon treatment is a heavily capitalized process, as indicated by the relatively large allocation for amortization. Note that in this instance, the carbon contactor system represents 65 percent of the total system capital cost. Design efforts should be directed at cost-saving approaches for contactor systems if significant overall capital cost savings are to be realized. Conversely, total costs are not very sensitive to changes in the cost of regeneration equipment.

Labor constitutes nearly one-half of the total system operation and maintenance costs for this example. Makeup carbon and power constitute the major additional costs.

Inspection of Figures 5-10 and 5-11 will confirm that required carbon dosage has little impact on total system capital cost, but of course directly affects operating costs and hence total annual cost.

SHEET 1 OF 2

TABLE 5–7

ESTIMATED GRANULAR ACTIVATED CARBON TREATMENT COST

PLANT ____________________

OWNER ____________________

PREPARED BY ____________________

DATE ____________ PROJECT NUMBER ____________

DESIGN DATA SUMMARY

DESIGN FLOWS: AVG. ______ MGD; PEAK ______ MGD

DESIGN CARBON DOSAGE: ________ LBS/MG, ________ LBS/DAY

DESIGN REGENERATION RATE ________ LBS/DAY ________ LBS/SQ. FT./DAY

FURNACE HEARTH AREA ________ SQ. FT.

TYPE AND NUMBER OF CONTACTORS ____________________

CAPACITY EACH CONTACTOR ______ MGD AT AVG. DESIGN FLOW, ______ CU. FT. EFFECTIVE VOLUME

PSEUDO CONTACT TIME ________ MINUTES (EMPTY CONTACTOR)

PRETREATMENT ____________________

____

ESTIMATED BID DATE: ____________

ESTIMATED EPA STP COST INDEX ____________ (NATIONAL) ____________ (LOCAL)

UNIT COSTS: POWER $ ______ /kWh; LABOR $ ______ /HR.; FUEL $ ______ /THERM; CARBON $ ______ /LB.

ESTIMATED CARBON MAKEUP ________ PERCENT

COMMENTS ____________________

____

____

____

CAPITAL COST ESTIMATE

ITEM	REFERENCE	CALCULATION NOTES	ESTIMATED COST
INFLUENT PUMP STATION	FIGURE ___	USE PEAK DESIGN FLOW	$ ______
CARBON CONTACTORS	FIGURE ___	USE AVG. DESIGN FLOW MULT. BY NO. OF CONTACTORS	______
CARBON REGENERATION SYSTEM	FIGURE ___		______
INITIAL CARBON CHARGE	FIGURE ___	ADJUST FOR CARBON COSTS DIFFERENT FROM $.33/LB.	______
ADJUSTMENTS			
____________		____________	______
____________		____________	______
____________		____________	______

SHEET 2 OF 2

TABLE 5-7 (Continued)

CAPITAL COST ESTIMATE (Continued)

ITEM	REFERENCE	CALCULATION NOTES	ESTIMATED COST
TOTAL CONSTRUCTION COST AT EPA STP INDEX = 175			$______
COST INDEX CORRECTIONS			
NATIONAL MULTIPLIER ______________			
LOCAL MULTIPLIER ______________			
ADJUSTED CONSTRUCTION COST			$______
TOTAL CAPITAL COST	FIGURE______		$______ ←
		(UNIT COST =	$______/MG)

OPERATION AND MAINTENANCE COST ESTIMATE

	REFERENCE	REFERENCE VALUE	ADJUSTMENT FACTOR		ESTIMATED ANNUAL COST
CARBON ADSORPTION	FIGURE___				
LABOR		$______/YR	(5.00)	$______/YR	
POWER			(0.020)	______	
MAINT. MATERIAL			( )	______	
TOTAL		$______/YR	( )		$______/YR
CARBON REGENERATION	FIGURE___				
LABOR		$______/YR	(5.00)	$______/YR	
MAKEUP CARBON			(8) (.33)	______	
FUEL			(.065)	______	
POWER			(.02)	______	
MAINT. MATERIALS			( )	______	
TOTAL AT FURNACE CAPACITY:		$______/YR	( )	$______/YR	
ADJUSTMENT TO DESIGN DOSAGE:					
TOTAL = LBS/DAY DOSAGE / LBS/DAY CAPACITY	($______/YR AT CAPACITY)				$______/YR

TOTAL OPERATION AND MAINTENANCE COST $______/YR ←

(UNIT COST = $______/MG)

TOTAL ANNUAL COST

CAPITAL AMORTIZATION:______PERCENT FOR______YEARS

CAPITAL RECOVERY FACTOR = ______ x $______ = $______/YR

TOTAL ANNUAL COST = $______/YR ←

(UNIT COST = $______/MG)

SHEET 1 OF 2

TABLE 5–7A

ESTIMATED GRANULAR ACTIVATED CARBON TREATMENT COST

PLANT Clear Creek Water Reclamation Plant

OWNER Unified Sanitary Authority, Clear Creek, California

PREPARED BY RLC

DATE 12 February 1973 **PROJECT NUMBER** W7618.6

DESIGN DATA SUMMARY

DESIGN FLOWS: AVG. 20 MGD; PEAK 40 MGD

DESIGN CARBON DOSAGE: 300 LBS/MG, 6,000 LBS/DAY

DESIGN REGENERATION RATE 12,000 LBS/DAY 45 LBS/SQ. FT./DAY

FURNACE HEARTH AREA 265 SQ. FT.

TYPE AND NUMBER OF CONTACTORS Upflow Countercurrent Packed, 15 (2 for storage of standby)

CAPACITY EACH CONTACTOR 1.5 MGD AT AVG. DESIGN FLOW, 4,200 CU. FT. EFFECTIVE VOLUME

PSEUDO CONTACT TIME 30 MINUTES (EMPTY CONTACTOR)

PRETREATMENT Activated Sludge, Lime Clarification, Filtration

ESTIMATED BID DATE: January 1974

ESTIMATED EPA STP COST INDEX 185 (NATIONAL) 190 (LOCAL)

UNIT COSTS: POWER $ .017 /kWh; LABOR $ 5.50/HR.; FUEL $ .060 /THERM; CARBON $ .34 /LB.

ESTIMATED CARBON MAKEUP 8 PERCENT

COMMENTS

CAPITAL COST ESTIMATE

ITEM	REFERENCE	CALCULATION NOTES	ESTIMATED COST
INFLUENT PUMP STATION	FIGURE 5-5	USE PEAK DESIGN FLOW	$ 380,000
CARBON CONTACTORS	FIGURE 5-2	USE AVG. DESIGN FLOW MULT. BY NO. OF CONTACTORS	2,000,000
CARBON REGENERATION SYSTEM	FIGURE 5-3		485,000
INITIAL CARBON CHARGE	FIGURE 5-1	ADJUST FOR CARBON COSTS DIFFERENT FROM $.33/LB.	405,000
ADJUSTMENTS			
Influent Pump Station		Split pump station costs between filters and carbon since they will operate in series	-190,000

TABLE 5–7A (Continued)

CAPITAL COST ESTIMATE (Continued)

ITEM	REFERENCE	CALCULATION NOTES	ESTIMATED COST
TOTAL CONSTRUCTION COST AT EPA STP INDEX = 175			$3,080,000
COST INDEX CORRECTIONS			
NATIONAL MULTIPLIER 1.06			
LOCAL MULTIPLIER 1.025			
ADJUSTED CONSTRUCTION COST			$3,346,000
TOTAL CAPITAL COST	FIGURE 5-6		$4,000,000 ←
		(UNIT COST =	$ 200,000/MG)

OPERATION AND MAINTENANCE COST ESTIMATE

	REFERENCE	REFERENCE VALUE	ADJUSTMENT FACTOR		ESTIMATED ANNUAL COST
CARBON ADSORPTION	FIGURE 5-9				
LABOR		$ 18,000/YR	$\left(\frac{5.50}{5.00}\right)$	$19,800 /YR	
POWER		46,000	$\left(\frac{0.017}{0.020}\right)$	39,000	
MAINT. MATERIAL		3,400	(1)	3,400	
TOTAL		$ * /YR	( )		$ 62,300/YR
CARBON REGENERATION	FIGURE 5-10				
LABOR		$130,000/YR	$\left(\frac{5.50}{5.00}\right)$	$143,000/YR	
MAKEUP CARBON		93,000	$\left(\frac{8}{8}\right)\left(\frac{.34}{.33}\right)$	96,000	
FUEL		9,000	$\left(\frac{.060}{.065}\right)$	8,300	
POWER		5,000	$\left(\frac{.017}{.02}\right)$	4,300	
MAINT. MATERIALS		4,800	( )	4,800	
TOTAL AT FURNACE CAPACITY:		$ * /YR	( )	$256,400/YR	
ADJUSTMENT TO DESIGN DOSAGE:					
TOTAL = $\frac{6{,}000 \text{ LBS/DAY DOSAGE}}{12{,}000 \text{ LBS/DAY CAPACITY}}$ ($ 256,400 /YR AT CAPACITY)					$ 128,200/YR

TOTAL OPERATION AND MAINTENANCE COST $ 190,300/YR ←

(UNIT COST = $ 29.60 /YR

TOTAL ANNUAL COST

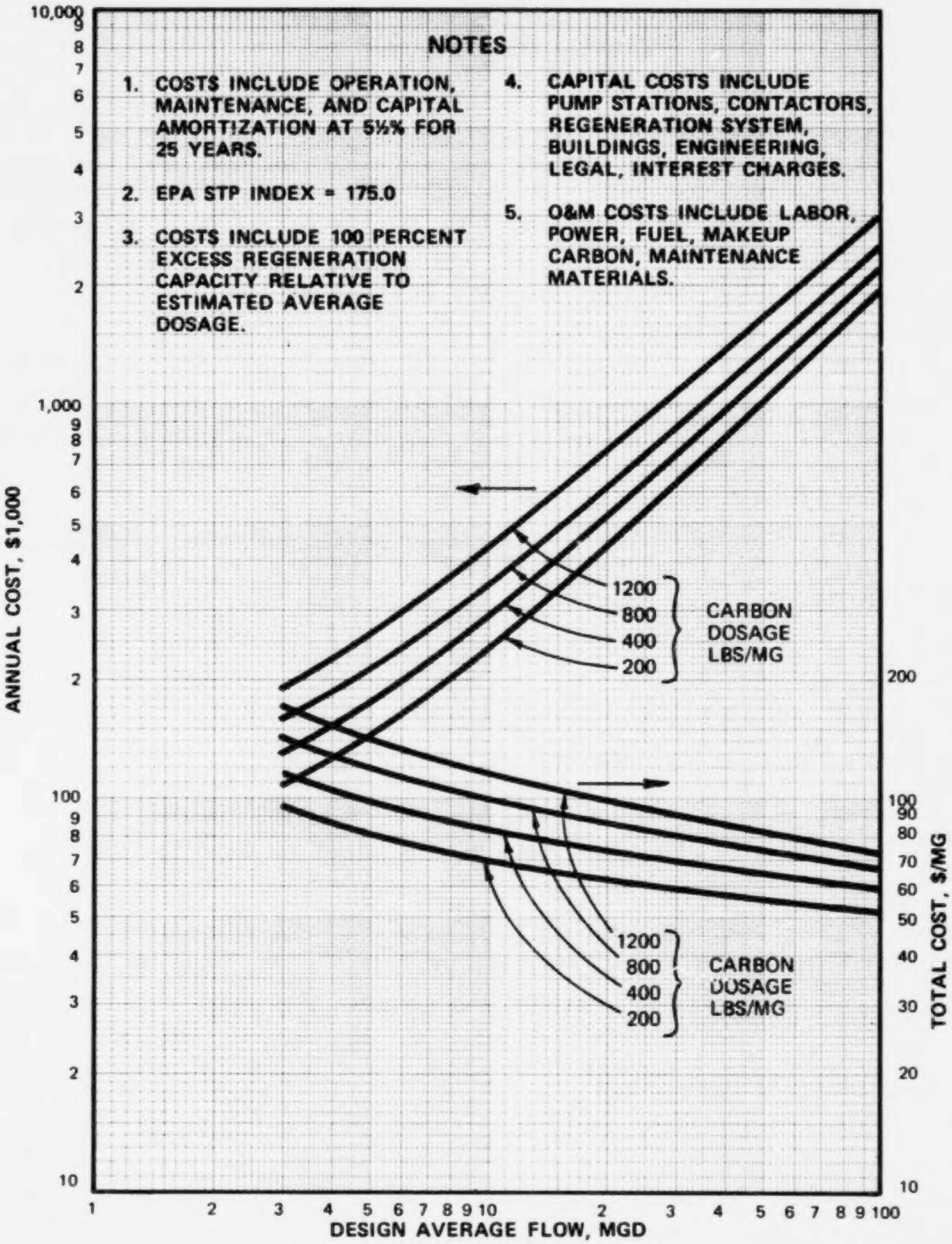
CAPITAL AMORTIZATION: 5½ PERCENT FOR 25 YEARS

CAPITAL RECOVERY FACTOR = .0745 × $4,000,000 = $ 298,000/YR

TOTAL ANNUAL COST = $ 488,300/YR ←

(UNIT COST = $ 69.90 /MG)

*NOTE: WHEN UNIT COSTS DO NOT VARY FROM THE UNIT COST BASES OF COST CURVES, THE TOTAL UNIT COST CURVE CAN BE USED DIRECTLY.



NOTES

1. COSTS INCLUDE OPERATION, MAINTENANCE, AND CAPITAL AMORTIZATION AT 5½% FOR 25 YEARS.
2. EPA STP INDEX = 175.0
3. COSTS INCLUDE 100 PERCENT EXCESS REGENERATION CAPACITY RELATIVE TO ESTIMATED AVERAGE DOSAGE.
4. CAPITAL COSTS INCLUDE PUMP STATIONS, CONTACTORS, REGENERATION SYSTEM, BUILDINGS, ENGINEERING, LEGAL, INTEREST CHARGES.
5. O&M COSTS INCLUDE LABOR, POWER, FUEL, MAKEUP CARBON, MAINTENANCE MATERIALS.

ANNUAL COST, $1,000
10,000
1,000
100
10
TOTAL COST, $/MG
200
100
90
80
70
60
50
40
30
20
10
DESIGN AVERAGE FLOW, MGD
1
2
3
4
5
6
7
8
9
10
100
1200
800
400
200
CARBON DOSAGE LBS/MG

FIGURE 5–11

TOTAL ANNUAL AND UNIT COSTS FOR CARBON TREATMENT

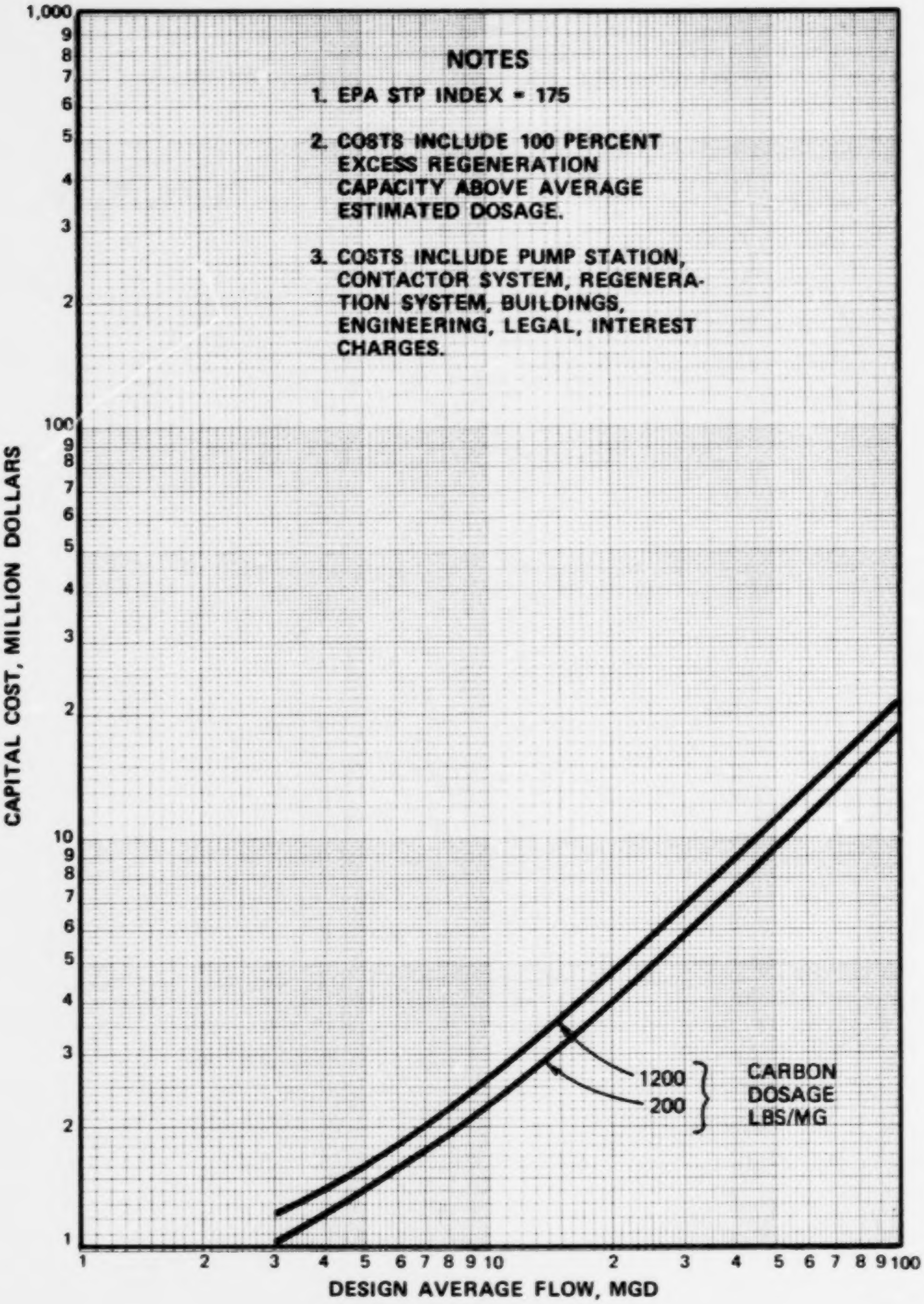


FIGURE 5–12

TOTAL CAPITAL COSTS FOR CARBON TREATMENT

TABLE 5-8
COST DISTRIBUTION FOR EXAMPLE CARBON TREATMENT SYSTEM

CAPITAL COSTS

Item	Percent of Total
Influent Pump Station	6
Carbon Contactor System	65
Carbon Inventory	13
Carbon Regeneration System	16
TOTAL	100

OPERATION AND MAINTENANCE COSTS

Item	
Adsorption System	
Labor	32
Power	63
Maintenance Materials	5
TOTAL	100
Regeneration System	
Labor	56
Makeup Carbon	37
Fuel	3
Power	2
Maintenance Materials	2
TOTAL	100
Combined System	
Labor	48
Makeup Carbon	25
Fuel	2
Power	22
Maintenance Material	3
TOTAL	100

TOTAL ANNUAL COST

Capital Amortization	61
Operation and Maintenance	39
TOTAL	100

5.9 Reference

1. Berthouex, P. M., *Evaluating Economy of Scale.* Journal WPCF, p. 211 (November, 1972).

CHAPTER 6
TYPICAL TREATMENT FACILITIES

6.1 Introduction

Methods for determining design criteria for equipment and carbon are outlined in Chapters 3 and 4. Also, several example designs utilizing either existing facilities or facilities under design were discussed in some detail in Chapter 3. Laboratory and pilot scale studies are described in some detail in Chapter 4. It is worth noting again that a well-planned and executed test program utilizing the wastewater to be treated is very important to the successful design and operation of a full-scale system.

The general range of design criteria currently being used in both tertiary and physical-chemical carbon treatment systems is shown in Table 6-1.

TABLE 6-1
GENERAL DESIGN PARAMETERS

Carbon Requirement	
Tertiary plant	200-400 lbs carbon per million gallons
PCT plant	500-1,800 lbs carbon per million gallons
Hydraulic Loading	2-10 gpm/sq ft
Contact Time (empty bed basis)	10-50 minutes
Backwash Rate	15-20 gpm/sq ft
Contactor Configuration	gravity or pressure vessels steel or concrete construction
Flow Configuration	upflow or downflow one stage or multi-stage

6.2 Current Plant Design, Construction, and Operation

Facilities for the treatment of municipal wastewaters have been divided into two categories: tertiary treatment plants and physical-chemical treatment plants. Information on tertiary treatment plants currently under design or construction or in operation is summarized in Table 6-2. Flow diagrams for the tertiary plants are shown on Figures 6-1 through 6-12. Similar information for physical-chemical treatment plants is summarized in Table 6-3 and Figures 6-13 through 6-22.

TABLE 6–2

TERTIARY TREATMENT PLANTS

SITE	STATUS 1973	DESIGN ENGINEER	AVERAGE PLANT CAPACITY (MGD)	CONTACTOR TYPE	NO. OF CONTACTORS IN SERIES	CONTACT TIME(1) (MIN.)	HYDRAULIC LOADING (GPM/SQ.FT.)	TOTAL CARBON DEPTH (FT.)	CARBON SIZE	EFFLUENT REQUIREMENTS(2) (OXYGEN DEMAND)
1. Arlington, Virginia	Design	Alexander Potter Assoc.	30	Downflow Gravity	1	38	2.9	15	8 x 30	BOD < 3 mg/l
2. Colorado Springs, Colo.	Operating Dec. '70 to Present	Arthur B. Chafet & Assoc.	3	Downflow	2	30	5	20	8 x 30	BOD < 2 mg/l
3. Dallas, Texas	Design	URS Forest & Cotton	100	Upflow Packed	1	10	8	10	8 x 30	BOD <10 mg/l BOD < 5 mg/l (by 1980)
4. Fairfax County, Va.	Design	Alexander Potter Assoc.	36	Downflow Gravity	1	36	3	15	8 x 30	BOD < 3 mg/l
5. Los Angeles, Calif.	Design	City of Los Angeles	5(3)	Downflow Gravity	2	50	4	26	8 x 30	COD <12 mg/l
6. Montgomery County, Md.	Design	CH2M/Hill	60	Upflow Packed	1	30	6.5	26	8 x 30	BOD < 1 mg/l COD <10 mg/l
7. Occoquan, Va.	Design	CH2M/Hill	18	Upflow Packed	1	30	5.8	24	8 x 30	BOD < 1 mg/l COD <10 mg/l
8. Orange County, Calif.	Construction	Orange County Water District	15	Upflow Packed	1	30	5.8	24	8 x 30	COD <30 mg/l
9. Piscataway, Md.	Operating Mar. '73 to Present	Roy F. Weston	5	Downflow Pressure	2	37	6.5	32	8 x 30	BOD < 5 mg/l
10. St. Charles, Missouri	Construction	Moran and Cooke	5.5	Downflow Gravity	1	30	3.7	15	8 x 30	
11. South Lake Tahoe, Calif.	Operating Mar. '68 to Present	CH2M/Hill	7.5	Upflow Packed	1	17	6.2	14	8 x 30	BOD < 5 mg/l COD <30 mg/l
12. Windhoek, South Africa	Operating Oct. '68 to Present	National Institute for Water Research Pretoria, So. Africa	1.3	Downflow Pressure	2	30	3.8	15	12 x 40	COD <10 mg/l

(1) Empty bed (superficial) contact time for average plant flow.

(2) BOD: Biochemical oxygen demand
COD: Chemical oxygen demand

(3) 50 mgd ultimate capacity

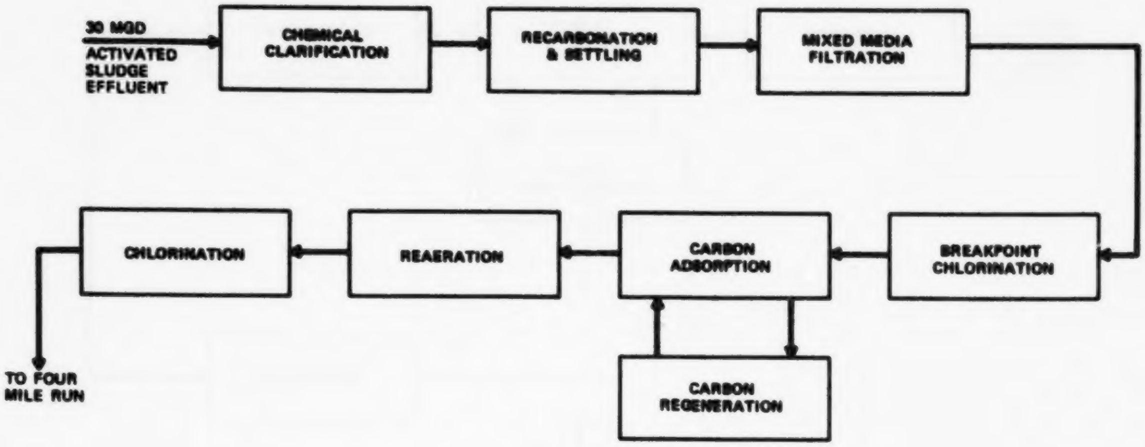

30 MGD
ACTIVATED SLUDGE EFFLUENT
CHEMICAL CLARIFICATION
RECARBONATION & SETTLING
MIXED MEDIA FILTRATION
BREAKPOINT CHLORINATION
CARBON ADSORPTION
REAERATION
CHLORINATION
CARBON REGENERATION
TO FOUR MILE RUN

FIGURE 6–1

TERTIARY TREATMENT SCHEMATIC –
ARLINGTON COUNTY, VIRGINIA

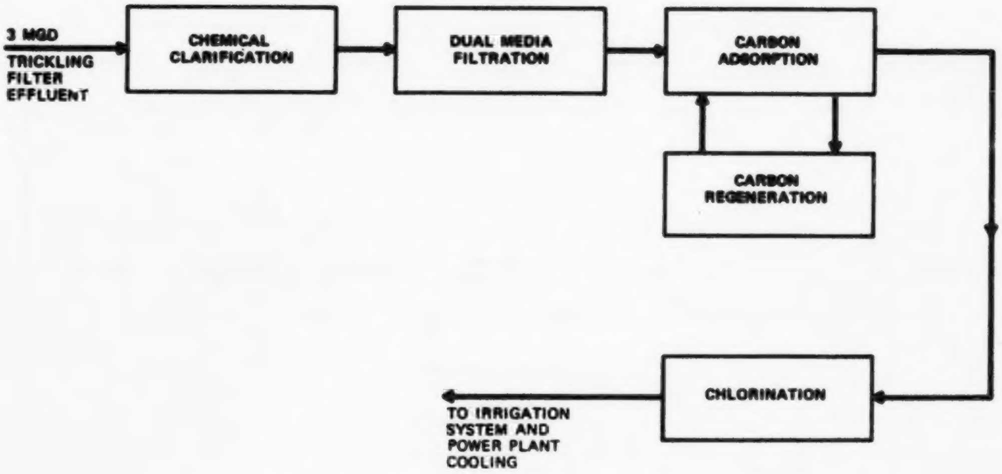

3 MGD
TRICKLING FILTER EFFLUENT
CHEMICAL CLARIFICATION
DUAL MEDIA FILTRATION
CARBON ADSORPTION
CARBON REGENERATION
CHLORINATION
TO IRRIGATION SYSTEM AND POWER PLANT COOLING

FIGURE 6–2

TERTIARY TREATMENT SCHEMATIC –
COLORADO SPRINGS, COLORADO

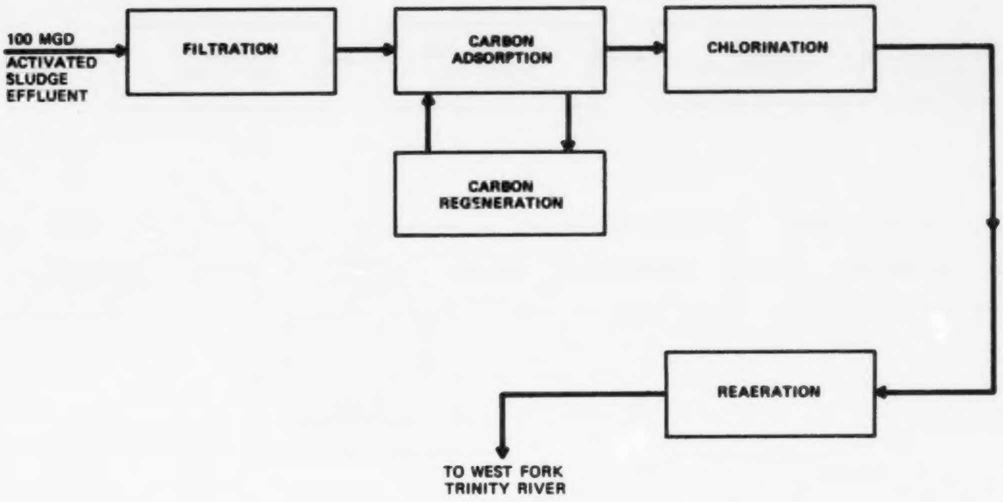

100 MGD
ACTIVATED SLUDGE EFFLUENT
FILTRATION
CARBON ADSORPTION
CHLORINATION
CARBON REGENERATION
REAERATION
TO WEST FORK TRINITY RIVER

FIGURE 6–3

TERTIARY TREATMENT SCHEMATIC –
DALLAS, TEXAS (TRINITY RIVER AUTHORITY)

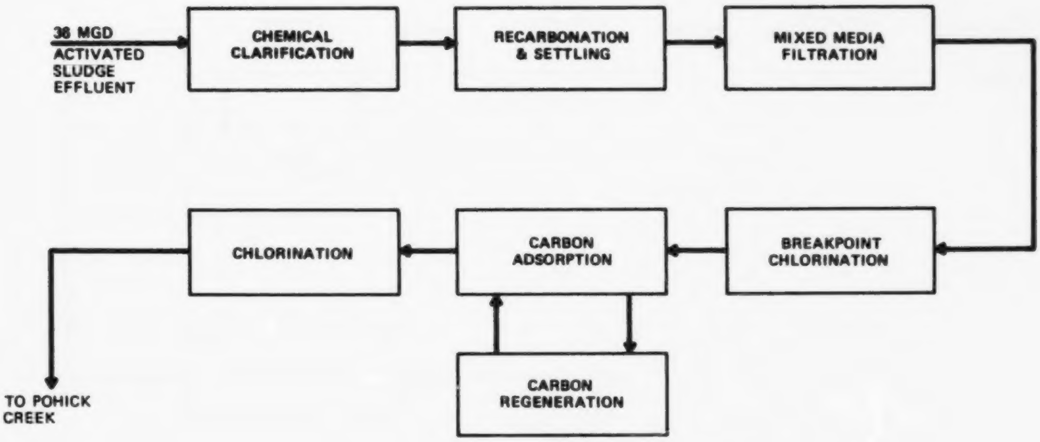

36 MGD
ACTIVATED SLUDGE EFFLUENT
CHEMICAL CLARIFICATION
RECARBONATION & SETTLING
MIXED MEDIA FILTRATION
BREAKPOINT CHLORINATION
CARBON ADSORPTION
CHLORINATION
CARBON REGENERATION
TO POHICK CREEK

FIGURE 6–4

TERTIARY TREATMENT SCHEMATIC –
FAIRFAX COUNTY, VIRGINIA (LOWER POTOMAC PLANT)

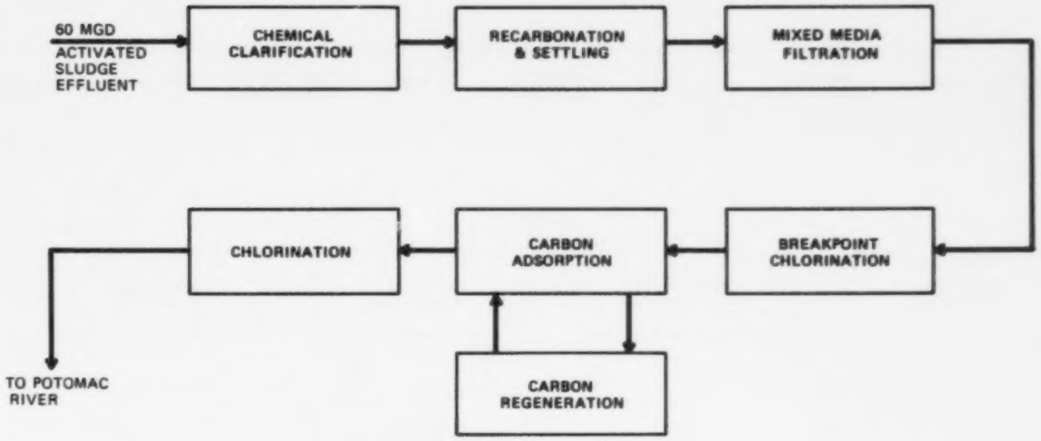

60 MGD
ACTIVATED SLUDGE EFFLUENT
CHEMICAL CLARIFICATION
RECARBONATION & SETTLING
MIXED MEDIA FILTRATION
BREAKPOINT CHLORINATION
CARBON ADSORPTION
CHLORINATION
CARBON REGENERATION
TO POTOMAC RIVER

FIGURE 6–5

TERTIARY TREATMENT SCHEMATIC – MONTGOMERY COUNTY, MARYLAND

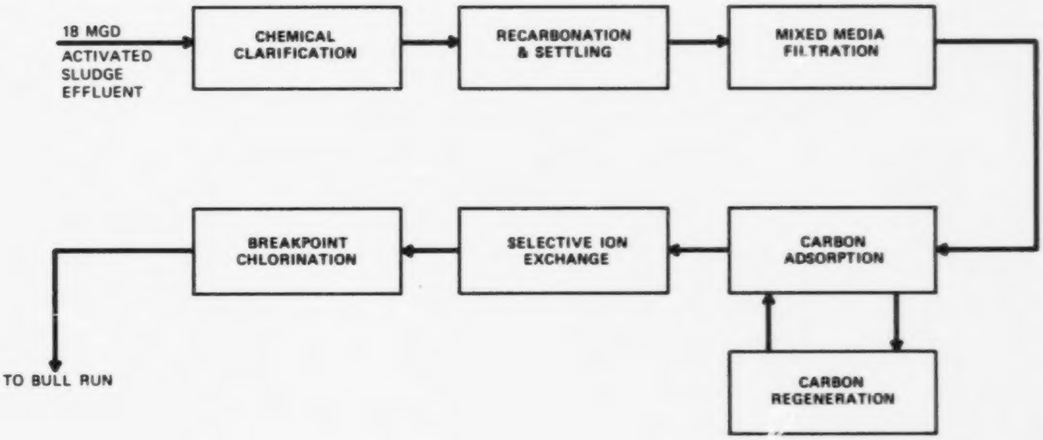

18 MGD
ACTIVATED SLUDGE EFFLUENT
CHEMICAL CLARIFICATION
RECARBONATION & SETTLING
MIXED MEDIA FILTRATION
CARBON ADSORPTION
SELECTIVE ION EXCHANGE
BREAKPOINT CHLORINATION
CARBON REGENERATION
TO BULL RUN

FIGURE 6–6

TERTIARY TREATMENT SCHEMATIC – UPPER OCCOQUAN SEWERAGE AUTHORITY, VIRGINIA

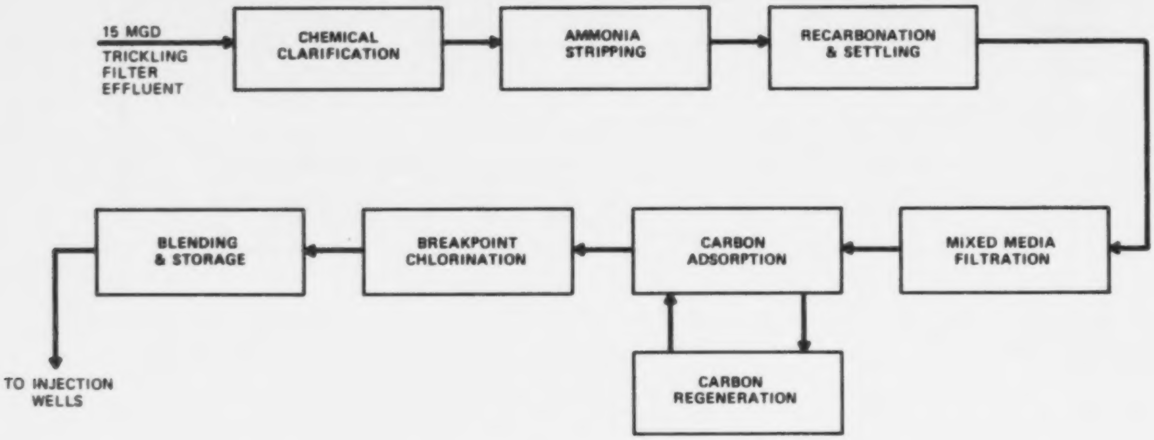

15 MGD
TRICKLING FILTER EFFLUENT
CHEMICAL CLARIFICATION
AMMONIA STRIPPING
RECARBONATION & SETTLING
MIXED MEDIA FILTRATION
CARBON ADSORPTION
CARBON REGENERATION
BREAKPOINT CHLORINATION
BLENDING & STORAGE
TO INJECTION WELLS

FIGURE 6–7

TERTIARY TREATMENT SCHEMATIC –
ORANGE COUNTY, CALIFORNIA

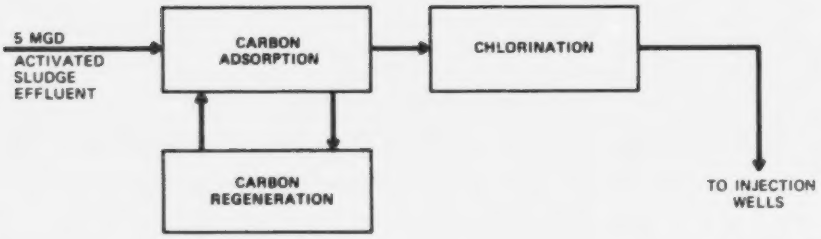

5 MGD
ACTIVATED SLUDGE EFFLUENT
CARBON ADSORPTION
CARBON REGENERATION
CHLORINATION
TO INJECTION WELLS

FIGURE 6–8

TERTIARY TREATMENT SCHEMATIC –
LOS ANGELES, CALIFORNIA

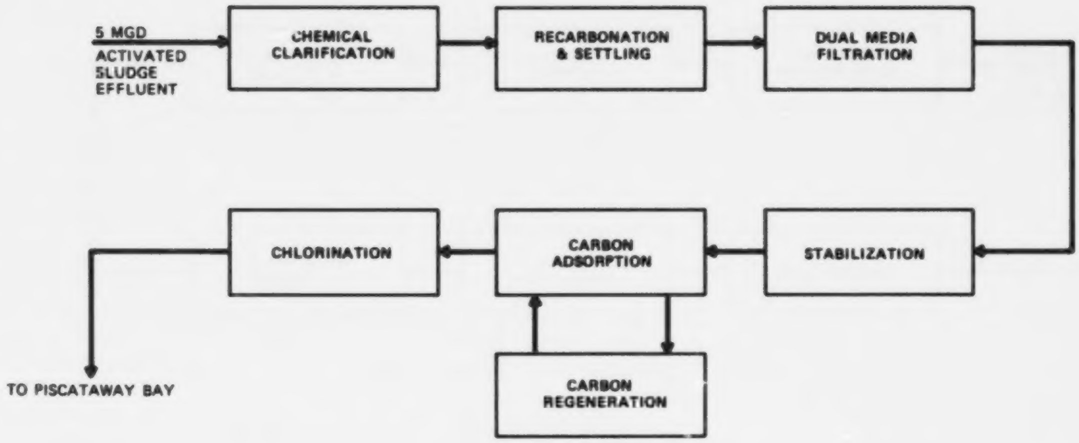

5 MGD
ACTIVATED SLUDGE EFFLUENT
CHEMICAL CLARIFICATION
RECARBONATION & SETTLING
DUAL MEDIA FILTRATION
STABILIZATION
CARBON ADSORPTION
CHLORINATION
CARBON REGENERATION
TO PISCATAWAY BAY

FIGURE 6–9

TERTIARY TREATMENT SCHEMATIC – PISCATAWAY, MARYLAND

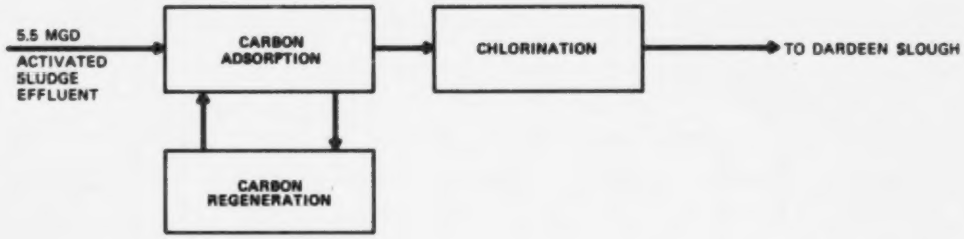

5.5 MGD
ACTIVATED SLUDGE EFFLUENT
CARBON ADSORPTION
CHLORINATION
TO DARDEEN SLOUGH
CARBON REGENERATION

FIGURE 6–10

TERTIARY TREATMENT SCHEMATIC – ST. CHARLES, MISSOURI

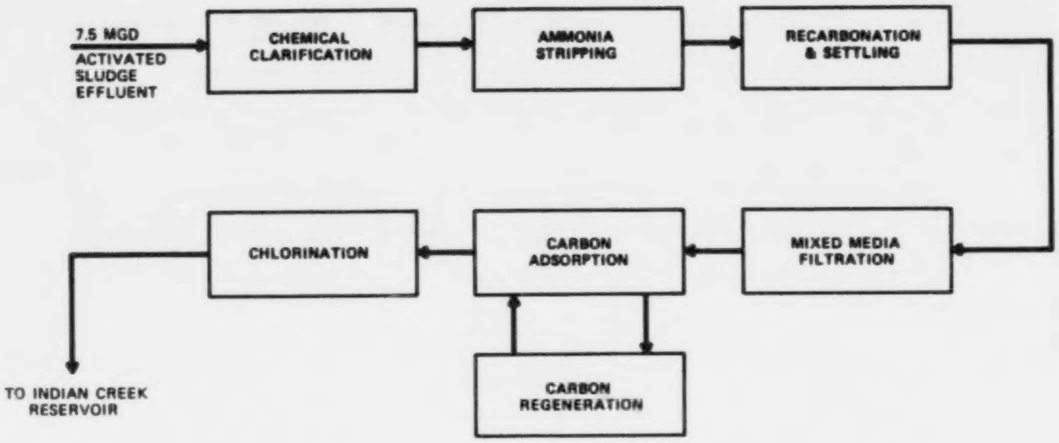

7.5 MGD
ACTIVATED SLUDGE EFFLUENT
CHEMICAL CLARIFICATION
AMMONIA STRIPPING
RECARBONATION & SETTLING
MIXED MEDIA FILTRATION
CARBON ADSORPTION
CARBON REGENERATION
CHLORINATION
TO INDIAN CREEK RESERVOIR

FIGURE 6–11

TERTIARY TREATMENT SCHEMATIC – SOUTH LAKE TAHOE, CALIFORNIA

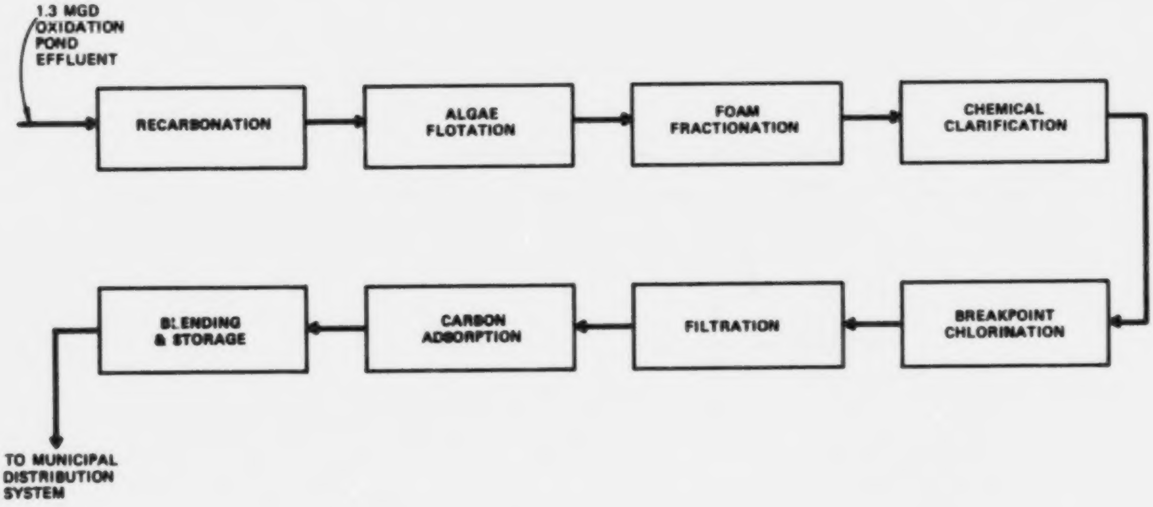

1.3 MGD
OXIDATION POND EFFLUENT
RECARBONATION
ALGAE FLOTATION
FOAM FRACTIONATION
CHEMICAL CLARIFICATION
BREAKPOINT CHLORINATION
FILTRATION
CARBON ADSORPTION
BLENDING & STORAGE
TO MUNICIPAL DISTRIBUTION SYSTEM

FIGURE 6–12

TERTIARY TREATMENT SCHEMATIC – WINDHOEK, SOUTH AFRICA

TABLE 6–3

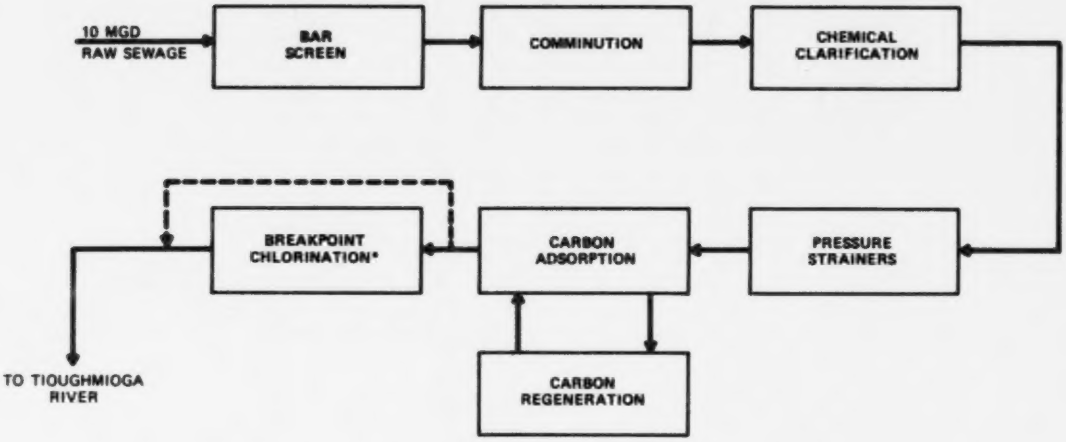
PHYSICAL-CHEMICAL TREATMENT PLANTS

SITE	STATUS 1973	DESIGN ENGINEER	AVERAGE PLANT CAPACITY (MGD)	CONTACTOR TYPE	NO. OF CONTACTORS IN SERIES	CONTACT TIME(1) (MIN.)	HYDRAULIC LOADING (GPM/SQ.FT.)	TOTAL CARBON DEPTH (FT.)	CARBON SIZE	EFFLUENT REQUIREMENTS(2) (OXYGEN DEMAND)
1. Cortland, N.Y.	Design	Stearns & Wheler	10	Downflow Pressure	1 or 2	30	4.3	17	8 x 30	TOD < 35 mg/l
2. Cleveland Westerly, Ohio	Design	Engineering-Science	50	Downflow Pressure	1	35	3.7	17	8 x 30	BOD < 15 mg/l
3. Fitchburg, Mass.	Construction	Camp Dresser & McKee	15	Downflow Pressure	1	35	3.3	15.5	8 x 30	BOD < 10 mg/l
4. Garland, Texas	Design	URS Forest & Cotton	30(3)	Upflow Downflow	2	30	2.5	10	8 x 30	BOD < 10 mg/l
5. LeRoy, New York	Design	Lozier Engineers	1	Downflow Pressure	2	27	7.3	26.8	12 x 40	BOD < 10 mg/l
6. Niagara Falls, N.Y.	Design	Camp Dresser & McKee	48	Downflow Gravity	1	20	3.3	9	8 x 30	COD < 112 mg/l
7. Owosso, Michigan	Design	Ayres, Lewis, Norris & May	6	Upflow Packed	2	36	6.2	30	12 x 40	BOD < 7 mg/l
8. Rosemount, Minn.	Construction	Banister, Short, Elliot, Hendrickson, and Associates	0.6	Upflow Downflow Pressure	3 (max.)	66 (max.)	4.2	36 (max.)	12 x 40	BOD < 10 mg/l
9. Rocky River, Ohio	Construction	Willard Schade & Assoc.	10	Downflow Pressure	1	26	4.3	15	8 x 30	BOD < 15 mg/l
10. Vallejo, Calif.	Design	Kaiser Engineers	13	Upflow Expanded	1	26	4.6	16	12 x 40	BOD < 45 mg/l (90% of time)

(1) Empty bed (superficial) contact time for average plant flow

(2) BOD: Biochemical oxygen demand
COD: Chemical oxygen demand
TOD: Total oxygen demand

(3) 90 mgd ultimate capacity


10 MGD
RAW SEWAGE
BAR SCREEN
COMMINUTION
CHEMICAL CLARIFICATION
PRESSURE STRAINERS
CARBON ADSORPTION
BREAKPOINT CHLORINATION*
CARBON REGENERATION
TO TIOUGHMIOGA RIVER

*USED ON PART OF FLOW WHEN NECESSARY TO MEET TOTAL OXYGEN DEMAND REQUIREMENTS.

FIGURE 6– 13

PHYSICAL CHEMICAL TREATMENT SCHEMATIC – CORTLAND, NEW YORK

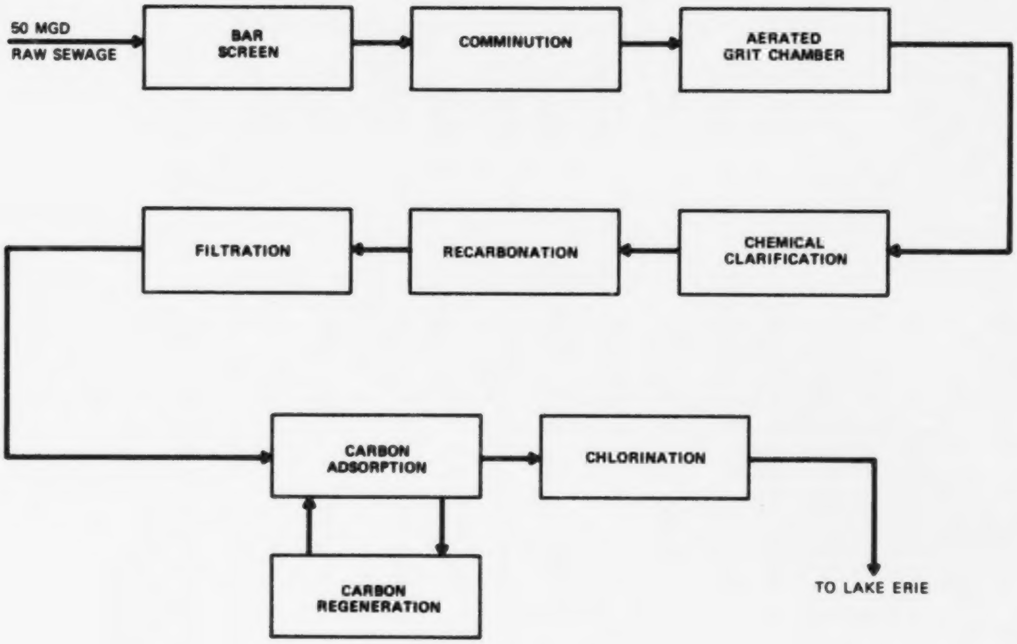

50 MGD
RAW SEWAGE
BAR SCREEN
COMMINUTION
AERATED GRIT CHAMBER
CHEMICAL CLARIFICATION
RECARBONATION
FILTRATION
CARBON ADSORPTION
CHLORINATION
CARBON REGENERATION
TO LAKE ERIE

FIGURE 6–14

PHYSICAL CHEMICAL TREATMENT SCHEMATIC
CLEVELAND WESTERLY, OHIO

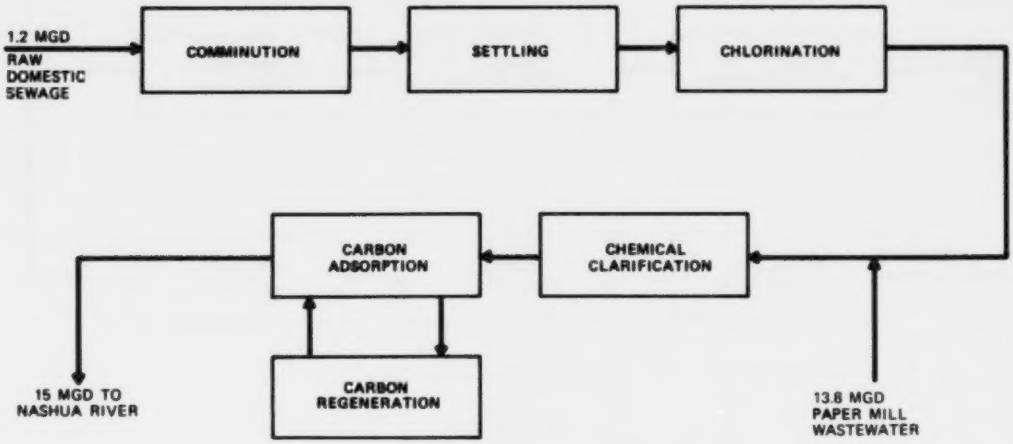

1.2 MGD RAW DOMESTIC SEWAGE
COMMINUTION
SETTLING
CHLORINATION
CHEMICAL CLARIFICATION
CARBON ADSORPTION
CARBON REGENERATION
15 MGD TO NASHUA RIVER
13.8 MGD PAPER MILL WASTEWATER

FIGURE 6–15

PHYSICAL CHEMICAL TREATMENT SCHEMATIC – FITCHBURG, MASSACHUSETTS

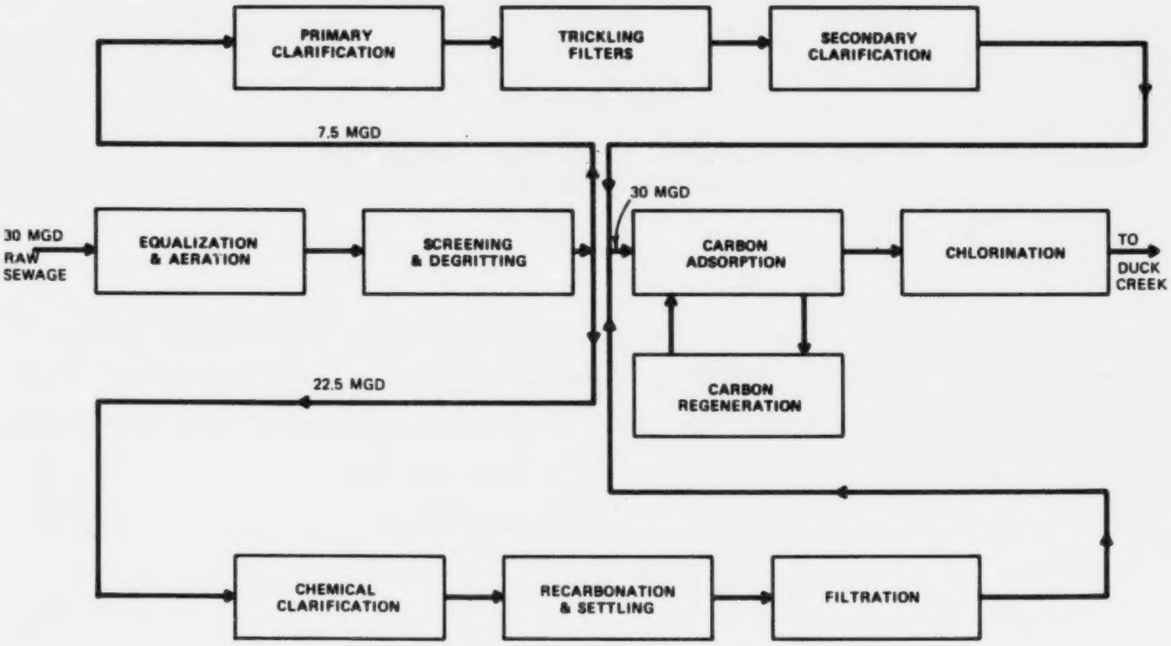

PRIMARY CLARIFICATION
TRICKLING FILTERS
SECONDARY CLARIFICATION
7.5 MGD
30 MGD RAW SEWAGE
EQUALIZATION & AERATION
SCREENING & DEGRITTING
30 MGD
CARBON ADSORPTION
CHLORINATION
TO DUCK CREEK
CARBON REGENERATION
22.5 MGD
CHEMICAL CLARIFICATION
RECARBONATION & SETTLING
FILTRATION

FIGURE 6–16

PHYSICAL CHEMICAL TREATMENT SCHEMATIC – GARLAND, TEXAS

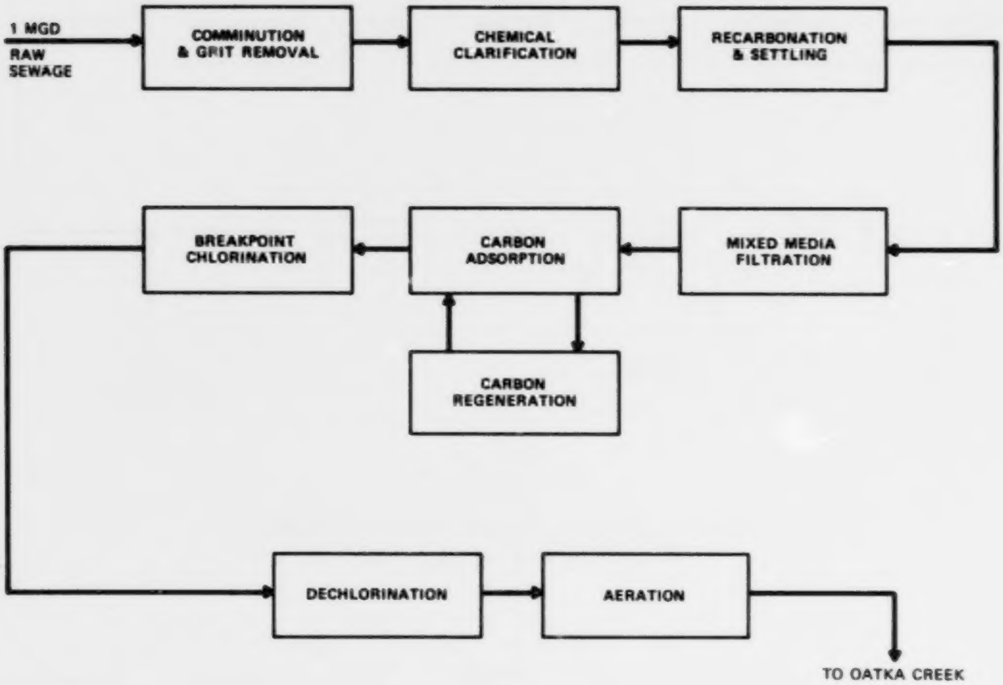

1 MGD
RAW
SEWAGE
COMMINUTION & GRIT REMOVAL
CHEMICAL CLARIFICATION
RECARBONATION & SETTLING
MIXED MEDIA FILTRATION
CARBON ADSORPTION
BREAKPOINT CHLORINATION
CARBON REGENERATION
DECHLORINATION
AERATION
TO OATKA CREEK

FIGURE 6–17

PHYSICAL CHEMICAL TREATMENT SCHEMATIC –
LeROY, NEW YORK

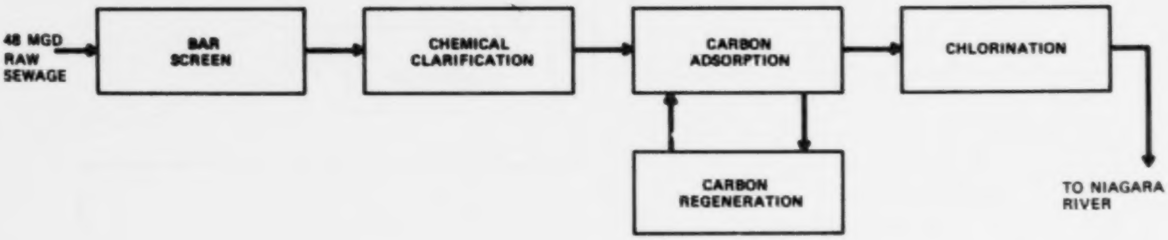

48 MGD
RAW
SEWAGE
BAR SCREEN
CHEMICAL CLARIFICATION
CARBON ADSORPTION
CHLORINATION
CARBON REGENERATION
TO NIAGARA RIVER

FIGURE 6–18

PHYSICAL CHEMICAL TREATMENT SCHEMATIC –
NIAGARA FALLS, NEW YORK

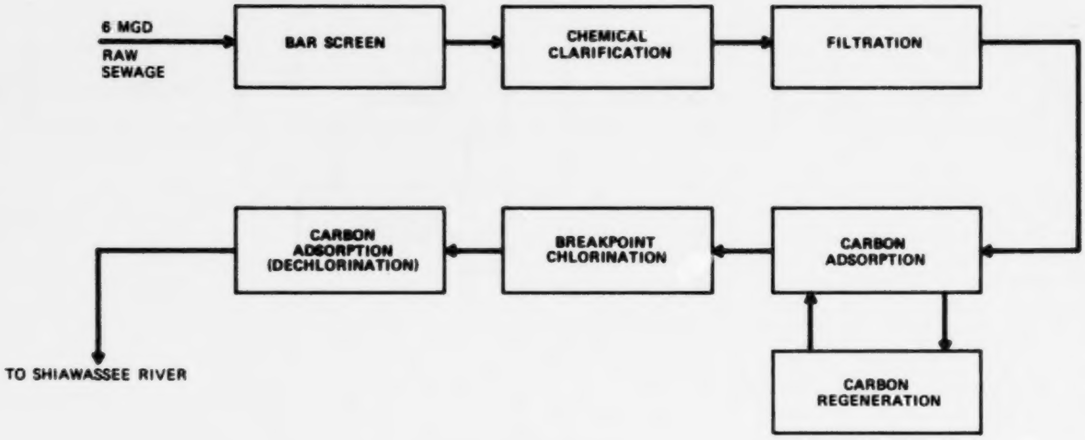

6 MGD
RAW SEWAGE
BAR SCREEN
CHEMICAL CLARIFICATION
FILTRATION
CARBON ADSORPTION
BREAKPOINT CHLORINATION
CARBON ADSORPTION (DECHLORINATION)
TO SHIAWASSEE RIVER
CARBON REGENERATION

FIGURE 6– 19

PHYSICAL CHEMICAL TREATMENT SCHEMATIC – OWOSSO, MICHIGAN

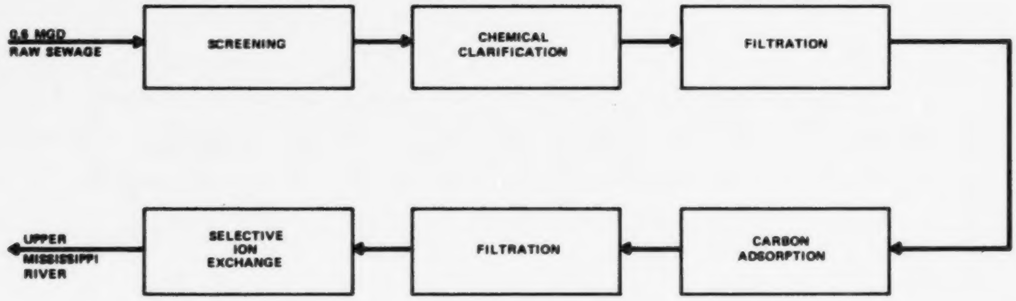

0.6 MGD
RAW SEWAGE
SCREENING
CHEMICAL CLARIFICATION
FILTRATION
CARBON ADSORPTION
FILTRATION
SELECTIVE ION EXCHANGE
UPPER MISSISSIPPI RIVER

FIGURE 6–20

PHYSICAL CHEMICAL TREATMENT SCHEMATIC – ROSEMOUNT, MINNESOTA

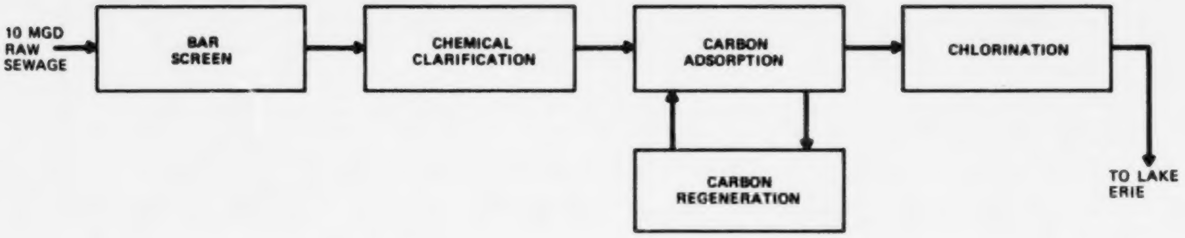

10 MGD RAW SEWAGE
BAR SCREEN
CHEMICAL CLARIFICATION
CARBON ADSORPTION
CHLORINATION
CARBON REGENERATION
TO LAKE ERIE

FIGURE 6–21

PHYSICAL CHEMICAL TREATMENT SCHEMATIC – ROCKY RIVER, OHIO

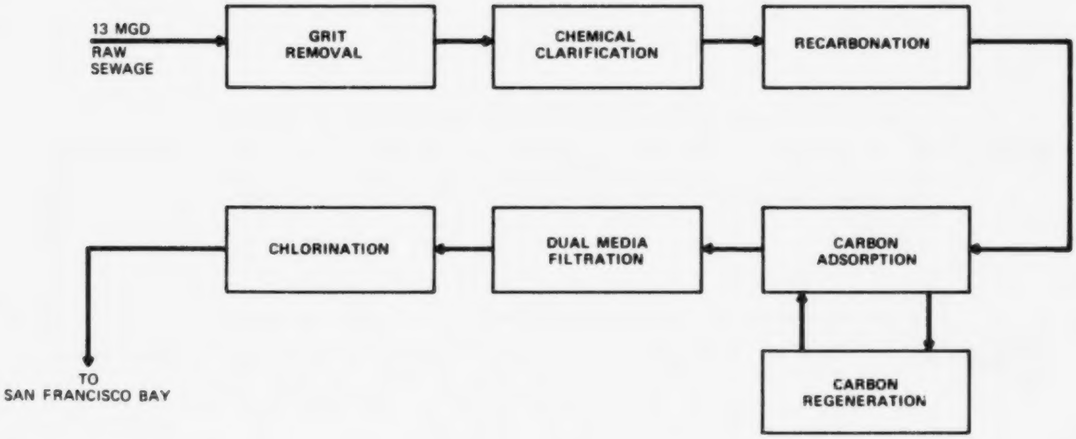

13 MGD RAW SEWAGE
GRIT REMOVAL
CHEMICAL CLARIFICATION
RECARBONATION
CARBON ADSORPTION
DUAL MEDIA FILTRATION
CHLORINATION
CARBON REGENERATION
TO SAN FRANCISCO BAY

FIGURE 6–22

PHYSICAL CHEMICAL TREATMENT SCHEMATIC VALLEJO, CALIFORNIA

6.2.1 Tertiary Treatment Plants

There were four full-scale tertiary treatment plants in operation in early 1973 which utilize granular activated carbon in the treatment process:

1. South Lake Tahoe, California–This 7.5 mgd facility treats activated sludge effluent and has been operating continuously and successfully since March 1968. The design criteria and operating results from this plant have been reported in several other publications [1, 2, 3]. The plant effluent requirements and the water quality at various points in the treatment process are shown in Tables 6-4 and 6-5. Data pertaining to the activated carbon systems are shown in Tables 6-6 through 6-9.

2. Windhoek, South Africa–This 1.3 mgd plant receives highly treated secondary effluent and processes this wastewater for subsequent use in the city's municipal water system. It has been operating successfully since October 1968. The pilot studies and results of the full-scale plant operation have been reported [4, 5, 6]. The quality of water at various points in the treatment plant is shown in Table 6-10.

3. Colorado Springs, Colorado–This 3 mgd tertiary treatment plant has been operating since December 1970. The secondary effluent supplied to this tertiary treatment plant is from an overloaded filter system; however, facilities are under construction to enlarge and upgrade secondary treatment. Some difficulty was experienced in start-up of the chemical clarification and solids handling system and it was several months before the tertiary facilities were operating normally. Some of the test work preliminary to the design of this plant has been reported [7].

4. Piscataway, Maryland–This 5 mgd plant began start-up operations in early 1973.

Two other tertiary treatment plants are currently under construction: one in St. Charles, Missouri, and another in Orange County, California. The plant in Orange County is scheduled for operation in June, 1974 and the design criteria have been reported [8,9]. Typical wastewater quality during the pilot study is shown in Table 6-11. The regulatory agency effluent requirements are shown in Table 6-12. The detailed design specifications have been completed for tertiary treatment plants in Arlington, Virginia, and Fairfax County, Virginia; and detailed design is in progress on tertiary plants in Occoquan, Virginia, and Montgomery County, Maryland. The preliminary design and project report has been completed for tertiary plants in Dallas, Texas, and Los Angeles, California.

TABLE 6–4

WATER QUALITY REQUIREMENTS AND PERFORMANCE DATA AT SOUTH LAKE TAHOE

DESCRIPTION	REQUIREMENTS				PLANT PERFORMANCE		
	ALPINE(1) CO.	LAHONTAN R.W.Q.C.B.(2) (% OF TIME)			(% OF TIME)		
		50	80	100	50	80	100
MBAS (mg/l), less than	0.5	0.3	0.5	1.0	0.19	0.35	0.35
BOD (mg/l), less than	5	3	5	10	1.0	2.5	3.9
COD (mg/l), less than	30	20	25	50	9	10	22
S.S. (mg/l), less than	2	1	2	4	0	0	0
Turbidity (JTU), less than	5	3	5	10	0.4	0.5	1.3
Phosphorus, (mg/l), less than		No Requirements			0.06	0.12	0.27
pH (units)	6.5–8.5	6.5–9.0			6.6–8.7		
Coliform, MPN/100 ml (3)	Adequately Disinfected	Median 2.0 Maximum Number Consecutive Sample >23, 2			Median 2.0 Number of Consecutive Samples >23, 0 (none)		

(1) Alpine Co. is location of Indian Creek Reservoir.

(2) Lahontan Regional Water Quality Control Board.

(3) All 30 samples collected during November, 1969, were found to be free of coliform organisms.

TABLE 6–5

WATER QUALITY AT VARIOUS STAGES OF TREATMENT AT SOUTH LAKE TAHOE

QUALITY PARAMETER	RAW WASTEWATER	EFFLUENT					
		PRIMARY	SECONDARY	CHEMICAL CLARIFIER	FILTER	CARBON	CHLORINATED FINAL
BOD (mg/l)	140	100	30		3	1	0.7
COD (mg/l)	280	220	70		25	10	10
SS (mg/l)	230	100	26	10	0	0	0
Turbidity (JTU)	250	150	15	10	0.3	0.3	0.3
MBAS (mg/l)	7	6	2.0		0.5	0.10	0.10
Phosphorus (mg/l)	12	9	6	0.7	0.10	0.10	0.10
Coliform (MPN/100 ml)	50 million	15 million	2.5 million		50	50	< 2.0

TABLE 6–6

CARBON EFFICIENCY PER REGENERATION PERIOD AT SOUTH LAKE TAHOE NOVEMBER 1968 THROUGH JANUARY 1971

PARAMETER	AVERAGE	MAXIMUM	MINIMUM
Carbon Dosage (lbs. regenerated/million gallons treated)(1)	207	418	111
Iodine Number(2)			
Spent Carbon	583	633	497
Regenerated Carbon	802	852	743
Apparent Density (gm/ml)(2)			
Spent Carbon	0.571	0.618	0.544
Regenerated Carbon	0.487	0.491	0.478
Percent Ash(2)			
Spent Carbon	6.4	7.0	5.8
Regenerated Carbon	6.8	7.2	5.8
Chemical Oxygen Demand			
Percent Removal	49.9	63.3	30.1
Lbs. COD Applied	28,250	54,970	15,680
Lbs. COD Applied per MG	162	254	105
Lbs. COD Removed per MG	81	149	32
Lbs. COD Applied per lb. Carbon Regenerated(1)	0.78	1.56	0.52
Lbs. COD Removed per lb. Carbon Regenerated(1)	0.39	0.71	0.16
Methylene Blue Active Substances (MBAS)			
Percent Removal	77.0	93.0	58.0
Lbs. MBAS Applied	995	1,675	457
Lbs. MBAS Applied per MG	5.7	10.7	2.6
Lbs. MBAS Removed per MG	4.4	8.2	1.6
Lbs. MBAS Applied per lb. Carbon Regenerated(1)	0.027	0.045	0.012
Lbs. MBAS Removed per lb. Carbon Regenerated(1)	0.021	0.039	0.007

(1) Based on cu. ft. of carbon fed to furnace at 30 lbs/cu.ft.

(2) November 1968 through November 1970.

TABLE 6-7
CARBON FURNACE PARAMETERS PER REGENERATION PERIOD AT SOUTH LAKE TAHOE NOVEMBER 1968 THROUGH NOVEMBER 1970

Parameter	Average	Maximum	Minimum
Furnace Feed Rate(1) (lbs/hr)	176	266	139
Fuel Requirements(2) (BTU/lb carbon)	2900	4510	1820
Hearth Temperatures (degrees F)			
No. 4 Hearth	1650	1460	1720
No. 6 Hearth	1670	1560	1740

(1) Amount fed to furnace per hr at 30 lbs/cu ft

(2) Natural gas requirements per lb of carbon fed to furnace at 860 BTU/cu ft and 18-20 psia

TABLE 6-8
FURNACE OPERATING CONDITIONS FOR FOUR BATCH REGENERATION CYCLES AT SOUTH LAKE TAHOE

COLUMN	CC-5	CC-5	CC-5	CC-8
CYCLE	First	Second	Third	Fourth
BATCH REGENERATION DATE	12/68	1/70	11/70	7/70
FURNACE FEED (lbs/hr)	286	164	146	142
GAS CONSUMPTION (BTU/lb)	1980	2710	3330	3470
HEARTH TEMPERATURE (degrees F)				
No. 4 Hearth	1660	1660	1700	1640
No. 6 Hearth	1650	1660	1700	1730

TABLE 6-9
CARBON LOSSES DURING BATCH REGENERATION PERIODS AT SOUTH LAKE TAHOE(1)

Regeneration Period (2)	Carbon Loss
May 1969	2.5%
Feb. 1970	6.2%
June 1970	5.9%
July 1970	8.6%

(1) Included regeneration of first cycle makeup carbon.

(2) About 1,200 cu ft of carbon is included in a regeneration period.

TABLE 6–10

WATER QUALITY AT VARIOUS STAGES OF TREATMENT AT WINDHOEK

DETERMINATION	RAW WATER	PRIMARY FLOTATION	LIME, CHLORINE, AND SEDIMENTATION	SAND FILTRATION	ACTIVATED CARBON FILTRATION
Total N (mg/l)	35	32	15	14	13
Organic N (mg/l)	3.2	1.3	0.9	0.7	Nil
Ammonia N (mg/l)	14.9	14.0	0.2	0.3	0.1
Oxides of N (mg/l)	17	17	14	13	13
Phosphates, as PO_4(mg/l)	10	Nil	Nil	Nil	Nil
ABS (mg/l)	8	7	4	4	0.7
BOD_5 (mg/l)	30	4	1	1	0.3
Sulfate, as SO_4 (mg/l)	108	228	220	220	220
pH	8.5	7.1	8.0	8.0	8.0

TABLE 6–11

WATER QUALITY AT PILOT PLANT AT ORANGE COUNTY, CALIFORNIA

CONSTITUENT	CONCENTRATION (mg/l)	
	INFLUENT	EFFLUENT
Calcium	70–110	80
Magnesium	20–45	2
Sodium	240–260	240–260
Potassium	20–35	20–35
Bicarbonate	200–450	250
Sulfate	270–350	270–350
Chloride	300–350	300–350
Phosphate	20–25	1
Nitrogen		
Organic	5–15	1
Ammonia	15–30	2
Nitrite	1	1
Nitrate	1	1
Total Dissolved Solids	1,200–1,400	1,000–1,100
Suspended Solids	30–80	1
BOD	30–80	2
COD	100–200	10–30
Methylene Blue		
Active Substance	3–4	0.1

TABLE 6-12
EFFLUENT REQUIREMENTS FOR TERTIARY TREATMENT PLANT AT ORANGE COUNTY, CALIFORNIA

Constituent	Maximum Concentration (mg/l)
Ammonium	1.0
Sodium	110.0
Total Hardness ($CaCO_3$)	220.0
Sulfate	125.0
Chloride	120.0
Total Nitrogen (N)	10.0
Fluoride	0.8
Boron	0.5
MBAS	0.5
Hexavalent Chromium	0.05
Cadmium	0.01
Selenium	0.01
Phenol	0.001
Copper	1.0
Lead	0.05
Mercury	0.005
Arsenic	0.05
Iron	0.3
Manganese	0.05
Barium	1.0
Silver	0.05
Cyanide	0.2
pH	6.5-8.0
Electrical Conductivity	900 mhos/cm
Taste	None
Odor	None
Foam	None
Color	None
Filter Effluent Turbidity	1.0 JTU
Carbon Adsorption Column Effluent COD	30 mg/l
Chlorine Contact Basin Effluent	Free Chlorine residual.

6.2.2 Physical-Chemical Treatment Plants

There are no full-scale physical-chemical treatment plants currently in operation. Three full-scale physical-chemical treatment plants are currently under construction. One in Fitchburg, Massachusetts, will treat a combined domestic sewage and paper mill processing waste. Others, in Rocky River, Ohio, and Rosemount, Minnesota, will treat domestic sewage. Other physical-chemical treatment plants in the detail design stage are Cortland, N. Y.; Cleveland Westerly, Ohio; LeRoy, N. Y.; Garland, Texas; Niagara Falls, N. Y.; Owosso, Michigan; and Vallejo, California.

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APPENDIX A
GLOSSARY OF TERMS USED WITH GRANULAR CARBON

ABRASION NUMBER–The abrasion number of granular carbon is a measure of the resistance of the particles to degrading on being mechanically abraded. It is measured by contacting a carbon sample with steel balls in a pan on a Ro-Tap machine. The abrasion number is the ratio of the final average (mean) particle diameter to the original average (mean) particle diameter (determined by screen analysis) times 100.

ACTIVATED CARBON–Carbon which is "activated" by high-temperature heating with steam or carbon dioxide producing an internal porous particle structure. The total surface area of granular activated carbon is estimated to be about 1,000 m^2/gm.

ADSORBATE–The material, e.g., color bodies, taste and odor compounds, which is adsorbed on an activated carbon or other adsorbent.

ADSORBENT–A material, such as activated carbon, upon which adsorption takes place.

ADSORPTION–The adhesion of an extremely thin layer of molecules (of gas, liquid) to the surfaces of solids (granular activated carbons, for instance) or liquids with which they are in contact.

ADSORPTION ISOTHERMS–A measurement of the adsorptive capacity of an adsorbent as a function of the concentration, or pressure, of the adsorbing material at a given temperature. It is defined as the constant temperature relationship between amount adsorbed per unit weight of adsorbent and the equilibrium concentration, or partial pressure.

APPARENT DENSITY–The weight per unit volume of a homogeneous activated carbon. To assure uniform packing of a granular carbon during measurement, a vibrating trough is used to fill the measuring device.

ASH–The mineral constituent of activated carbon. It is normally defined as a weight percent basis after a given amount of sample is reduced to ash.

AVERAGE (MEAN) PARTICLE DIAMETER–This is a weighed average diameter of a granular carbon. A screen analysis is run and the average particle diameter calculated by multiplying the weight of each fraction by its average diameter, adding the products, and dividing by the total weight of the sample. The average diameter of each fraction is taken as the size midway between the sieve opening through which the fraction has passed and the sieve opening on which the fraction has passed and the sieve opening on which the fraction was retained.

BACKWASH–The process by which water is forced through a filtration bed in the direction opposite to the normal flow, usually upward. During backwashing, the bed expands allowing the material which has been previously filtered out to be washed away.

BACKWASH BED EXPANSION–The expansion that occurs when a filter bed is being backwashed, usually expressed as a percentage of the backwashed and settled bed.

BED DENSITY, BACKWASHED AND DRAINED–The weight per unit volume on a dry basis of a bed of activated carbon that has been backwashed and drained. This value is usually lower than the corresponding apparent density due to the classification according to size of the carbon granules during backwashing.

BED DEPTH(HEIGHT)–The depth of carbon, expressed in length units, which is parallel to the flow of the stream and through which the stream must pass.

BED DIAMETER–The diameter of a cylindrical carbon column, measured perpendicular to the stream flow.

BIOCHEMICAL OXYGEN DEMAND (BOD)–This is a measure of the concentration of organic impurities, usually applied to wastewaters. It is the amount of oxygen required by bacteria while stabilizing, usually for five days, organic matter under aerobic conditions, expressed in mg/l.

BREAKTHROUGH CURVE–The relationship between the volume of liquid or gas treated in a carbon column and the concentration or partial pressure of the component being removed. This can be applied to color, taste and odor numbers, or other criteria of purity.

CARBON COLUMN–A column filled with granular activated carbon whose primary function is the preferential adsorption of a particular type or types of molecules.

CHEMICAL OXYGEN DEMAND (COD)–This is a measure of the amount of organic material in a sample expressed in mg/l of oxygen and is based on the ability of a strong oxidizing agent under acid conditions to oxidize organic material to carbon dioxide and water.

COLOR BODIES–Those complex molecules which impart color (usually undesirable) to a solution.

CONTACT TIME–The time required for the liquid to pass through a carbon column assuming that all the liquid passes through at the same velocity. It is equal to the volume of the empty bed divided by the flow rate.

COUNTERCURRENT OPERATION–Any contacting process, e.g., adsorption, where the flows of influent wastewater and solid absorbent proceed in opposite directions. The highest concentration of dissolved organics contacts the most nearly exhausted portion of the adsorbent, while the virgin adsorbent contacts only the lowest concentration of organics. The purpose of such a system is to take fullest advantage of the adsorptive capacity of the nearly exhausted adsorbent. See under Moving Bed.

CROSS-SECTIONAL BED AREA–The area of activated carbon through which the stream flow is perpendicular.

DESORPTION–The opposite of adsorption. A phenomenon where an adsorbed molecule leaves the surface of the adsorbent.

EDUCTOR–A device with no moving parts used to force an activated carbon water slurry through pipes to the desired location.

EFFECTIVE SIZE–The size of the particle that is coarser than 10 percent, by weight, of the material. That is, it is the size sieve which will permit 10 percent of the carbon sample to pass but will retain the remaining 90 percent. It is usually determined by the interpolation of a cumulative particle size distribution.

FIXED BED–An adsorption process in which liquid being treated is allowed to pass through a carbon column till the carbon becomes exhausted and the unit is removed from service and *completely* recharged with fresh carbon. The carbon remains *fixed* in position during the adsorption process.

FREEBOARD–The height to the top of the adsorption column, or wash through in the case of sand filters, above the surface of the carbon.

HARDNESS NUMBER–This is the Chemical Warfare Service (CWS) test. The hardness number is a measure of the resistance of a granular carbon to the degradation action of steel balls in a pan in a Ro-Top machine. It is calculated by using the weight of granular carbon retained on a particular sieve after the carbon has been in contact with steel balls.

HYDRAULIC LOADING–The quantity of flow passing through a column or packed bed expressed in the units of volume per unit time per unit area; e.g., gpm/sq ft (superficial velocity).

IODINE NUMBER–The iodine number is the milligrams of iodine adsorbed by one gram of carbon at an equilibrium filtrate concentration of 0.02N iodine. It is measured by contacting a single sample of carbon with an iodine solution and extrapolating to 0.02N by an assumed isotherm slope. Iodine number can be correlated with ability to adsorb low molecular weight substances.

LOSSES ON REGENERATION–The loss of original carbon during regeneration due to the burning off or mechanical breaking of the carbon. Losses are usually 5-10 percent for coal-based carbons.

MACROPORE–The pores in activated carbon which are larger in diameter than 1,000 Å.

MAKEUP CARBON–Fresh granular activated carbon which must be added to an adsorption system after a regeneration cycle or when deemed necessary to keep the total amount of carbon adequate. This is to replace carbon lost during regeneration.

MESH SIZE–The particle size of granular activated carbon as determined by the U. S. Sieve Series. Particle size distribution within a mesh series is given in the specifications of the particular carbon.

METHYLENE BLUE NUMBER–The methylene blue number is the milligrams of methylene blue adsorbed by one gram of carbon in equilibrium with a solution of methylene blue having a concentration of 1.0 mg/l.

MICROPORE–The pores in activated carbon which are smaller in diameter than 1,000 Å.

MOISTURE–The percent by weight of water adsorbed on activated carbon.

MOLASSES DECOLORIZING INDEX (MDI) (DI)–This Westvaco method requires the same technique as for molasses value but differs in the method of calculation. A Spex-Mixer Mill is used for grinding. Approximately, it is the ratio of molasses color capacity of a carbon to that of a standard carbon times 10. The MDI can be correlated with the capacity to adsorb many high molecular weight substances.

MOLASSES NUMBER–The molasses number is calculated from the ratio of the optical densities of the filtrate of a molasses solution treated with a standard activated carbon and the activated carbon in question. This is a test method of Pittsburgh Activated Carbon Company.

MOLASSES VALUE (MV)–This is the usual Westvaco method wherein the molasses value is determined by optical density of a molasses residual filtrate after carbon treatment. A standard carbon and molasses is used as a base for comparison of adsorbabilities. A Spex-Mixer Mill is used for grinding.

MOVING (PULSED) BED–A moving bed incorporates an effective countercurrent operation within a single column. This is accomplished by the removal of spent carbon from one end of the carbon bed and the addition of carbon at the other end. The flow of liquid and carbon are in opposite directions, usually the carbon moves downward and the liquid upward.

OVERBURNING–Excessive burn-off during reactivation resulting in high losses of carbon.

PARALLEL COLUMNS–A treatment process in which the liquid being treated is split into several separate streams and each small stream is treated in one single carbon column.

PARTICLE DENSITY, WETTED IN WATER–The density of carbon in water assuming all pores to be filled with water. The value can be calculated by use of the real density of the activated carbon and the pore volume.

PARTICLE SIZE–Usually, this term refers to the sizes of the two screens, either in the U. S. Sieve Series or the Tyler Series between which the bulk of a carbon sample falls. For example, 8 x 30 means most of the carbon passes a No. 8 screen but is retained on a No. 30 screen.

PARTICLE SIZE DISTRIBUTION–The particle size distribution in a given sample is obtained by mechanically shaking a weighed amount of material through a series of test sieves. It is the series of weights retained between the series of sieves.

PHYSICAL-CHEMICAL TREATMENT (PCT) PLANT–A treatment sequence in which physical and chemical processes are used to the exclusion of explicit biological processes. This does not exclude incidental biological treatment obtained on filter media or adsorptive surfaces. In this sense, a PCT scheme is a substitute for conventional biological treatment. A PCT scheme following an existing biological plant may by contrast be called simply a tertiary plant, although it is also PCT in a general sense.

PORE SIZE DISTRIBUTION–A measure of the pore structure, which gives activated carbons their unique adsorptive properties. Cumulative distributions give the relationship between pore size, say diameter or radius, and volume in pores smaller, or larger, than that size. Derivative, or interval, distributions indicate the amount of volume in pores between certain close sizes. Pore size distributions in the micropores, or small pores, are calculated from nitrogen adsorption isotherms while distributions in the macropores are measured with the mercury penetrometer. Micropore distributions can be used to predict adsorptive capacities for different molecular weight substances. The macropore distributions can be correlated with rates of adsorption, important for many applications.

PORE VOLUME–The sum of the macro and micro pores in a carbon, or, in other words, the total pore volume. This is expressed as volume per unit weight.

PRESSURE DROP (HEADLOSS)–The drop of pressure across an adsorption column due to the resistance of the carbon particles to the flow of liquids or gases through the system.

REAL DENSITY–The density of the skeleton of a carbon particle. This is determined by helium or mercury displacement. It usually comes close to that for graphite.

REGENERATION–Restoration of sorptive capacity to a used adsorbent by chemical or thermal treatment.

RESIDENT (RETENTION) TIME–The theoretical length of time for a liquid to pass through a carbon column assuming all the liquid moves through with the same uniform velocity. It is equal to the volume of liquid in the column divided by the rate of flow. The volume of liquid in a carbon column is simply the total volume of the column times the void fraction.

SERIES COLUMNS–An adsorption process in which the effluent from a first column becomes the influent for a second column, the effluent from the second column becomes the influent for a third column, and so on.

SUPERFICIAL VELOCITY–The velocity of a liquid passing through a column or packed bed expressed in the units of volume per unit time per unit area; e.g., gpm/sq ft.

SURFACE AREA–This is the amount of surface area per unit weight of carbon. The surface area of activated carbon is usually determined from the nitrogen adsorption isotherm by the Brunauer, Emmett and Teller Method (BET Method). Surface area is usually expressed in square meters per gram of carbon.

THRESHOLD ODOR NUMBER–This test is based on a comparison with an odor-free water obtained by passing tap water through a column of activated carbon. The water under test is diluted with odor-free water until the odor is no longer detectable. The last dilution at which an odor is observed is the threshold odor number.

TOTAL ORGANIC CARBON (TOC)–The TOC is a measure of the amount of organic material in a water sample expressed in mg/l of carbon. It is measured with a Beckman Carbonaceous Analyzer or other instrument wherein the organic compounds are catalytically oxidized to CO_2 and measured by an infrared detector. This method is frequently being applied to wastewaters.

TURBIDITY–A cloudiness of a liquid due to finely divided material in suspension which may not be of sufficient size to be seen as individual particles by the naked eye, but which scatters the light in passage through the liquid. It is frequently measured in Jackson Turbidity Units (JTU).

UNIFORMITY COEFFICIENT–This is obtained by dividing the sieve opening in millimeters which will pass 60 percent of a sample by the sieve opening in millimeters which will pass 10 percent of the sample. These values are usually obtained by interpolation on a cumulative particle size distribution.

VOIDS IN PACKED BEDS–The volume between the carbon particles in a packed bed or column expressed as a percentage of the total bed (carbon) volume. For Westvaco granular carbons, the voids amount to about 40 percent.

WAVE FRONT–The wave front is the capacity gradient that exists in the critical bed depth. It outlines the gradual transition of the carbon from "Fresh" to "Spent."

APPENDIX B
CONTROL TESTS - CARBON ADSORPTION AND REGENERATION

This appendix contains test procedures that are of importance in examination of both spent and virgin granular activated carbon.

The tests on the following pages are listed in the order given below:

B. 1	Iodine Number
B. 2	Molasses Number
B. 3	Decolorizing Index
B. 4	Methylene Blue Number
B. 5	Hardness Number
B. 6	Abrasion Number (Ro-Tap)
B. 7	Abrasion Number (NBS)
B. 8	Apparent Density
B. 9	Sieve Analysis (Dry)
B.10	Effective Size and Uniformity Coefficient
B.11	Moisture
B.12	Total Ash

B.1 Iodine Number

The Iodine Number is defined as the milligrams of iodine adsorbed by one gram of carbon when the iodine concentration of the residual filtrate is 0.02 normal.

B.1.1 Reagents and Equipment

Hydrochloric Acid, 5 percent weight–To 550 ml of distilled water add 70 ml of reagent-grade concentrated hydrochloric acid (HCl).

Sodium Thiosulfate, 0.1 normal–Dissolve 25 grams of reagent-grade sodium thiosulfate ($Na_2S_2O_3$ $5H_2O$) in one (1) liter of freshly boiled distilled water. Add a few drops of chloroform to minimize bacterial decomposition of the thiosulfate solution. Standarize the thiosulfate solution against 0.100 normal potassium biniodate ($KH(IO_3)_2$). Prepare the 0.1000 normal $KH(IO_3)_2$ using primary standard quality $KH(IO_3)_2$ which has been dried overnight at 105 degrees C and cooled in a desiccator. Weigh 3.249 grams $KH(IO_3)_2$ and make-up to exactly one liter in a volumetric flask with distilled water. Store in a glass-stoppered bottle.

To 80 ml of distilled water add, with constant stirring, one ml of concentrated sulfuric acid (H_2SO_4), 10 ml of 0.1000 $KH(IO_3)_2$ solution and approximately one gram of potassium iodide (KI). Titrate the mixture immediately with the thiosulfate solution adding 2-3 drops of starch solution when the iodine fades to a light yellow color. Continue the titration by adding the thiosulfate dropwise until a drop produces a colorless solution. Record the volume of titrate used.

$$\text{Normality of sodium thiosulfate} = \frac{1.000}{\text{ml of } Na_2S_2O_3 \text{ consumed}}$$

Iodine Solution–Dissolve 12.7 grams of reagent-grade iodine (I_2) and 19.1 grams of potassium iodide in a small quantity, approximately 20 ml, of distilled water. (If excess water is used, materials will not go into solution.) Dilute to one (1) liter in a volumetric flask with distilled water. Store in a glass-stoppered bottle in a dark place or use in a dark bottle. To standarize the iodine solution, pipette 25.0 ml into a 250 ml Erlenmeyer flask and immediately titrate with the 0.1 normal thiosulfate solution. Add 2-3 drops of starch solution near the endpoint and continue titrating until solution is colorless. Record the volume of titrant used.

$$\text{Normality of iodine solution} = \frac{\text{ml of } Na_2S_2O_3 \text{ used} \times \text{normality } Na_2S_2O_3}{25}$$

Starch Solution–To 2.5 grams of starch (potato, arrowroot, or soluble), add a little cold water and grind in a mortar to a thin paste. Pour into one (1) liter of boiled distilled water, stir, and allow to settle. Use the clear supernatant. Preserve with 1.25 grams of salicylic acid per one (1) liter of starch solution.

Filter Paper–Whatman Folded No. 2V, 10.5 cm.

Spex-Mixer Mill–No. 8000 Spex-Mixer Mill and No. 8001 Grinding Vials, Spex Industries, Inc., 3800 Park Avenue, Metuchen, New Jersey.

B.1.2 Procedure

Grind a representative sample of carbon in a Spex-Mixer Mill (usually 70 seconds) until 90± 5 percent will pass a 325 mesh sieve (by wet sieve analysis). Load the Spex-Mixer Mill with a 5.5 ± 0.5 gram sample and use 64 one-fourth inch diameter smooth steel balls. An adequate sample of the pulverized carbon should then be dried at 140 degrees C for one (1) hour, or 110 degrees C for three (3) hours. A moisture balance can also be used.

Weigh 1.000 gram of the dried pulverized carbon (see Note 1) and transfer the weighed sample into a dry, glass-stoppered, 250 ml Erlenmeyer flask. To the flask add 10 ml of 5 percent wt. HCl acid and swirl until the carbon is wetted. Place the flask on hot plate, bring contents to boil and allow to boil for only 30 seconds.

After allowing the flask and contents to cool to room temperature, add 100 ml of standarized 0.1 normal iodine solution to the flask. Immediately stopper flask and shake contents vigorously for 30 seconds. Filter by gravity immediately after the 30-second shaking period through Whatman No. 2V filter paper. Discard the first 20 or 30 ml of filtrate and collect the remainder in a clean beaker. Do not wash the residue on the filter paper.

Mix the filtrate in the beaker with a stirring rod and pipette, 50 ml of the filtrate into a 250 ml Erlenmeyer flask. Titrate the 50 ml sample with standarized 0.1 normal sodium thiosulfate until the yellow color has almost disappeared. Add about 1 ml of starch solution and continue titration until the blue indicator color just disappears. Record the volume of sodium thiosulfate solution used.

Notes on Procedure

1. The capacity of a carbon for any adsorbate is dependent on the concentration of the adsorbate in the medium contacting the carbon. Thus, the concentration of the residual filtrate must be specified, or known, so that appropriate factors may be applied to correct the concentration to agree with the definition. The amount of sample to be used in the determination is governed by the activity of the carbon. If the residual filtrate normality (C) is not within the range 0.008N to 0.035N given in the Iodine Correction Table, the procedure should be repeated using a different weight of sample.

2. It is important to the test that the potassium iodide to iodine weight ratio is 1.5 to 1 in the standard iodine solution.

Calculation

$$\text{Iodine Number} = \frac{X}{m}D$$

$$\frac{X}{m} = \frac{A - (2.2B \times \text{ml of thiosulfate solution used})}{\text{Weight of sample (grams)}}$$

$$C = \frac{N_2 \times \text{ml of thiosulfate solution used}}{50}$$

X/m = mg iodine adsorbed per gram of carbon

N_1 = Normality of iodine solution

N_2 = Normality of sodium thiosulfate solution

A = $N_1 \times 12693.0$

B = $N_2 \times 126.93$

C = Residual filtrate normality

D = Correction factor (obtained from Table B-1)

TABLE B-1
IODINE CORRECTION FACTOR (D)

Residual Filtrate Normality (C)	.0000	.0001	.0002	.0003	.0004	.0005	.0006	.0007	.0008	.0009
.0080	1.1625	1.1613	1.1600	1.1575	1.1550	1.1538	1.1513	1.1500	1.1475	1.1463
.0090	1.1438	1.1425	1.1400	1.1375	1.1363	1.1350	1.1325	1.1300	1.1288	1.1275
.0100	1.1250	1.1238	1.1225	1.1213	1.1200	1.1175	1.1163	1.1150	1.1138	1.1113
.0110	1.1100	1.1088	1.1075	1.1063	1.1038	1.1025	1.1000	1.0988	1.0975	1.0963
.0120	1.0950	1.0938	1.0925	1.0900	1.0888	1.0875	1.0863	1.0850	1.0838	1.0825
.0130	1.0800	1.0788	1.0775	1.0763	1.0750	1.0738	1.0725	1.0713	1.0700	1.0688
.0140	1.0675	1.0663	1.0650	1.0625	1.0613	1.0600	1.0588	1.0575	1.0563	1.0550
.0150	1.0538	1.0525	1.0513	1.0500	1.0488	1.0475	1.0463	1.0450	1.0438	1.0425
.0160	1.0413	1.0400	1.0388	1.0375	1.0375	1.0363	1.0350	1.0333	1.0325	1.0313
.0170	1.0300	1.0288	1.0275	1.0263	1.0250	1.0245	1.0238	1.0225	1.0208	1.0200
.0180	1.0200	1.0188	1.0175	1.0163	1.0150	1.0144	1.0138	1.0125	1.0125	1.0113
.0190	1.0100	1.0088	1.0075	1.0075	1.0063	1.0050	1.0050	1.0038	1.0025	1.0025
.0200	1.0013	1.0000	1.0000	0.9988	0.9975	0.9975	0.9963	0.9950	0.9950	0.9938
.0210	0.9938	0.9925	0.9925	0.9913	0.9900	0.9900	0.9888	0.9875	0.9875	0.9863
.0220	0.9863	0.9850	0.9850	0.9838	0.9825	0.9825	0.9813	0.9813	0.9800	0.9788
.0230	0.9788	0.9775	0.9775	0.9763	0.9763	0.9750	0.9750	0.9738	0.9738	0.9725
.0240	0.9725	0.9708	0.9700	0.9700	0.9688	0.9688	0.9675	0.9675	0.9663	0.9663
.0250	0.9650	0.9650	0.9638	0.9638	0.9625	0.9625	0.9613	0.9613	0.9606	0.9600
.0260	0.9600	0.9588	0.9588	0.9575	0.9575	0.9563	0.9563	0.9550	0.9550	0.9538
.0270	0.9538	0.9525	0.9525	0.9519	0.9513	0.9513	0.9506	0.9500	0.9500	0.9488
.0280	0.9488	0.9475	0.9475	0.9463	0.9463	0.9463	0.9450	0.9450	0.9438	0.9438
.0290	0.9425	0.9425	0.9425	0.9413	0.9413	0.9400	0.9400	0.9394	0.9388	0.9388
.0300	0.9375	0.9375	0.9375	0.9363	0.9363	0.9363	0.9363	0.9350	0.9350	0.9346
.0310	0.9333	0.9333	0.9325	0.9325	0.9325	0.9319	0.9313	0.9313	0.9300	0.9300
.0320	0.9300	0.9294	0.9288	0.9288	0.9280	0.9275	0.9275	0.9275	0.9270	0.9270
.0330	0.9263	0.9263	0.9257	0.9250	0.9250					

B.2 Molasses Number

Molasses solutions are treated with pulverized activated carbon of unknown decolorizing capacity and with a standard carbon of known Molasses Number. The optical densities of the filtrates are measured and the Molasses Number of the unknown is calculated from the ratio of the optical densities and the standard value.

B.2.1 Reagents and Equipment

Standard Carbon–Small quantities of standard carbon are available from the Chemical Division, Westvaco Corporation.

Molasses Solution–Prepare by diluting 146 grams of blackstrap molasses with one (1) liter of distilled water. The weight of molasses to be used varies with the particular lot of molasses and is adjusted, if necessary, so that the standard carbon produces a filtrate with an optical density (percent transmission) of 0.38 to 0.42.

Any grade of commercial molasses which may be purchased will vary considerably in depth of color. The dilution of the initial solution to give the same final filtrate color with the standard carbon compensates for such variations. Once such an adjustment has been made on a given lot of molasses, the proper dilution may be made routinely. The molasses solution is stored in a refrigerator and any unused portion discarded after 24 hours.

A suitable grade of blackstrap molasses can be purchased from Refined Syrups, Yonkers, New York.

Spex-Mixer Mill - No. 8000 Spex-Mixer Mill and No. 8001 Grinding Vials, Spex-Industries, Inc., 3880 Park Avenue, Metchun, New Jersey.

Filter Paper Suspension–Prepare by mascerating 16 circles of Whatman No. 3, 7-cm filter paper in one (1) liter of distilled water.

Absorption Cell - Klett-Summerson, No. 902, 10-mm.

Immersion Plate - Klett-Summerson, No. 903, 7.5 mm.

B.2.2 Procedure

Grind a representative sample to carbon in a Spex-Mixer Mill until 90 ± 5 percent will pass a 325-mesh sieve (by wet sieve analysis). Load the Spex-Mixer Mill with a 5.5 ± 0.5 gram sample and use 64 one-fourth inch diameter smooth steel-balls. An adequate supply of the carbon should then be dried at 140 degrees C for one (1) hour or 110 degrees C for three (3) hours. Weigh 0.46 gram portions of pulverized standard carbon of known decolorizing capacity and unknown carbon and transfer to separate 400 ml beakers. Add 50.0 ml of molasses solution to each beaker and stir until the carbon is thoroughly wetted.

Place the beakers on hotplate and allow to boil for 30 seconds from time boiling commences.

Immediately after boiling, filter the samples by vacuum through a Buchner funnel, using Whatman No. 3 filter paper which has been previously coated by filtering 50 ml of the filter paper suspension (see Note 1). Discard the first 10 to 15 ml of the sample filtrate and collect the remainder.

Using a 2.5 mm effective light path and a 425 mμ (blue) filter, compare the optical densities of the samples against distilled water in a Fisher Electrophotometer or other suitable instrument (See Note 2).

Notes on Procedure

1. The Buchner funnels and precoated filter paper should be prepared beforehand so that no delay is encountered in filtering the samples. Discard the filtrate from the filter paper suspension before filtering the samples.

2. Since the Fisher Electrophotometer is not equipped with 2.5 mm cells, the cell holder was modified to accommodate the 10-mm, Klett-Summerson cell. A 2.5 mm effective light path is obtained by placing the cell with a 7.5 mm glass immersion plate.

Calculations

$$\text{Molasses Number} = \frac{K \times B}{A}$$

K = Molasses Value of Standard Carbon
A = Optical Density of Filtrate from Test Carbon
B = Optical Density of Filtrate from Standard Carbon

B.3 Decolorizing Index

Molasses solution is treated with different weights of a standard carbon of known Decolorizing Index. The optical densitites of the filtrate are measured and plotted with the known Decolorizing Index values to obtain a standard curve. A molasses solution is then treated with pulverized activated carbon of unknown decolorizing capacity. The optical density of the filtrate is measured and the Decolorizing Index is determined from the standard curve.

B.3.1 Reagents and Equipment

Blackstrap Molasses–This molasses is available only through the Chemical Division, Westvaco Corporation, as selection is required to obtain molasses which provides reproducible data from year to year.

Anhydrous Disodium Phosphate

Phosphoric Acid

Supercel Filter Aid

Standard D. I. Carbon–Small quantities of primary standard carbon are available from the Chemical Division, Westvaco Corporation.

Filter Cloth–A chain cloth, 32-inches wide, made by T. Shriver and Company, Harrison, New Jersey.

Electric Hot Plate–The hot plate is a Type H, 120 volts, 550 watts, made by Precision Scientific Company. This hot plate is used without the refractory top.

Klett-Summerson Colorimeter–A No. 54 green filter and a 10 ml Klett-Summerson absorption tube (12.5 mm light path) are used for reading the samples. The instrument is zeroed using distilled water.

The instrument should give approximately the following reading when using a 0.5 normal potassium dichromate ($K_2Cr_2O_7$) solution:

0.5 Normal Potassium Dichromate	Klett-Summerson Reading
20 Percent Dilution	155
60 Percent Dilution	280
100 Percent Dilution	350

Return instrument pointer to near zero after each reading.

Analytical Balance - Sensitivity to 0.5 milligram.

Spex-Mixer Mill - No. 8000 Spex-Mixer Mill and No. 8001 Grinding Vials, Spex Industries, Inc., 3880 Park Avenue, Metuchen, New Jersey.

Filter Paper - Whatman No. 5, 15 cm.

B.3.2 Preparation of Solutions

Buffer Solution–(8X)–104 grams anhydrous disodium phosphate (Na_2HPO_4) or equivalent weight of crystalline phosphate, are dissolved in about 500 millimeters of warm distilled water. When the phosphate is completely dissolved, make up to one liter with distilled water. Acidify with concentrated reagent-grade phosphoric acid to pH 6.5 ± 0.1. For preparation of larger quantities, multiples of these weights and volumes may be used.

Molasses Solution–Dilute 40 grams of the blackstrap molasses in about 50 ml (or amount necessary) of distilled water (approximately 25 degrees C). Add 125 ml of buffer solution, dilute to one liter with chilled distilled water (approximately 4 degrees C) and mix thoroughly. (Solution will be about 13 degrees C). However, if the molasses solution is to be used immediately the distilled water does not need to be chilled before using.

For preparation of larger quantities, multiples of these weights and volumes can be used.

A Buchner funnel fitted with a filter cloth, is precoated by slurrying Supercel filter aid with a portion of the blackstrap molasses solution and filtering. Use sufficient Supercel filter aid to provide a cake approximately one-half inch thick. After precoating, change funnel to a clean filter flask. Pour the solution, to which a small amount of Supercel has been added. The entire solution, is then filtered through the filter aid cake. (If necessary, this solution should be refiltered until it is clear.) If this solution is not to be used immediately, it must be refrigerated (at about 4 degrees C).

B.3.3 Preparation of Standard Curve

1. Weigh accurately (± 0.001 gram) the following weights of the ground† Standard D. I. carbon (dried at 140 degrees C for one (1) hour or 110 degrees C for three (3) hours) into 150 ml beakers: 0.200, 0.300, 0.400, 0.500, 0.600, 0.700, 0.900, and 1.00 gram.
2. Measure 50 ml of the molasses solution, using a graduated cylinder, and reading the bottom of the menicus.
3. Add 10 to 20 ml of the molasses solution to the weighed carbon. Swirl the contents of the beaker gently until the carbon is completely wetted. Use the remaining portion of the molasses solution to wash down the sides of the beaker.

---

† A ground sample is obtained by placing a 5.5 ± 0.5 gram sample of dried carbon in a Spex-Mixer Mill Containing 64 one-fourth inch diameter smooth steel balls until 90 ± 5 percent will pass a 325 mesh screen (by wet screen analysis).

4. Place the beaker on the hot plate and bring the sample to a boil (the solution should be brought to boiling in less than 200 seconds). Boil for 30 seconds and then remove sample from hot plate.

5. Filter immediately by gravity using a Whatman No. 5, 15 cm. filter paper (or equivalent). Allow all of the samples to filter.

6. Allow filtrate to cool to room temperature (approximately 25 degrees C).

7. Read the color of the samples, using the Klett-Summerson Colorimeter.

8. To prepare the Standard Curve, plot the Klett-Summerson readings of the samples (from Step 1) versus the assigned Decolorizing Index Numbers (listed in the following table) on semilogarithmic, 1 cycle x 70 divisions graph paper.

Weight of Standard D. I. Carbon	Assigned Decolorizing Index Number
0.200	6.5
0.300	8.6
0.400	11.2
0.500	14.0
0.600	16.9
0.700	19.9
0.800	23.0
0.900	27.0
1.00	30.8

Draw a straight curve line through these points. (See Figure B-1). A new standard curve will need to be prepared for molasses solution which has been stored at 4 degrees C for longer than 16 hours.

B.3.4 Preparation of Samples to be Tested

1. Weigh 0.460 ± 0.001 gram of the dried ground carbon sample to be tested, and transfer to a 150 ml beaker.

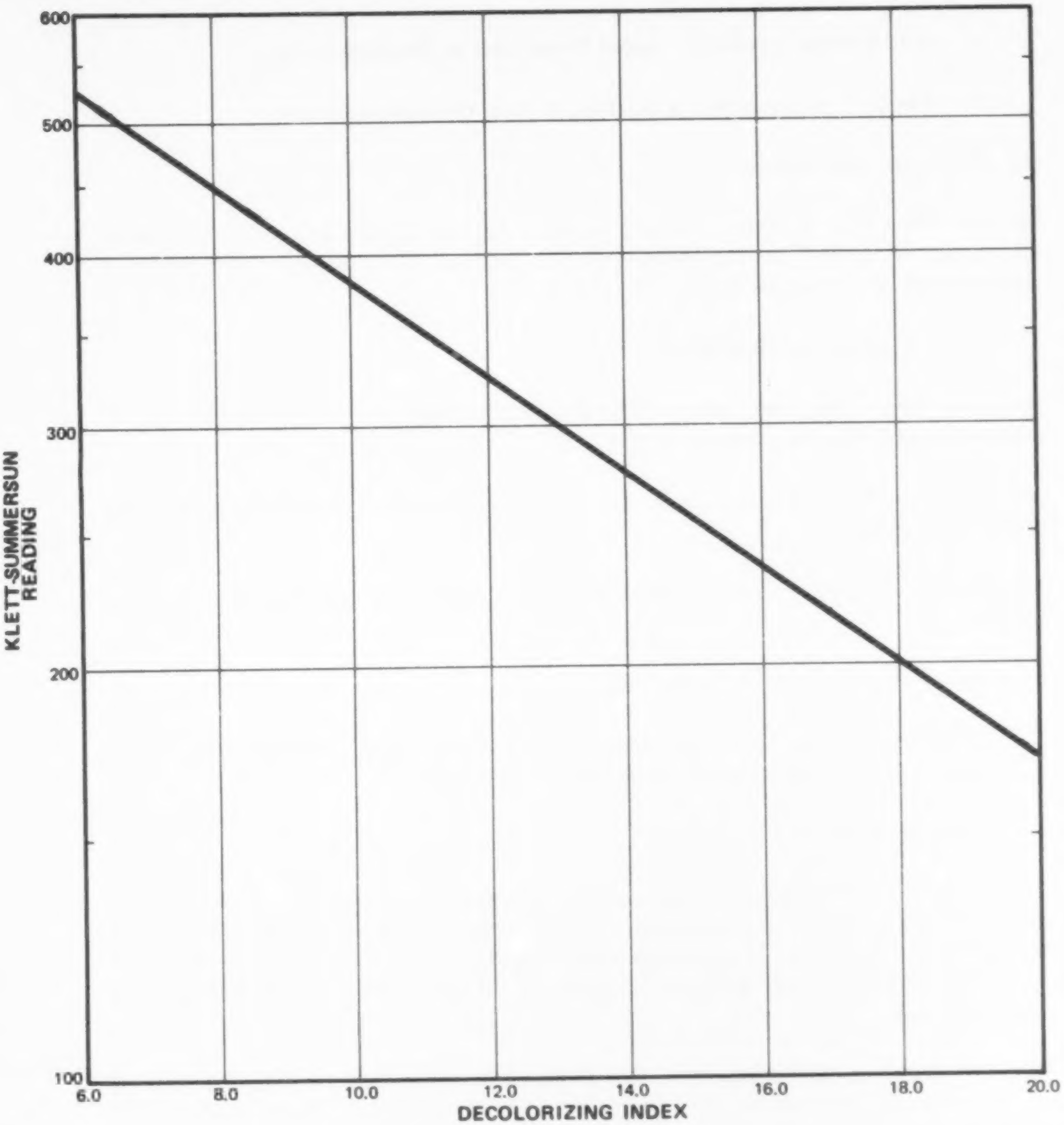


FIGURE B–1

EXAMPLE OF STANDARD CURVE

2. Follow Steps 2 through 7 under Preparation of Standard Curve.

3. The D. I. of the carbon is determined from the Standard Curve.

B.4 Methylene Blue Number

The Methylene Blue Number is defined as the milligrams of methylene blue adsorbed by one gram of carbon in equilibrium with a solution of methylene blue having a concentration of 1.0 mg per liter.

B.4.1 Reagents and Equipment

Methylene Blue - Zinc-free, American Cyanamid Company. Dry the methylene blue to constant weight. Prepare solutions of 20.00 and 1.00 g/l concentration.

Colorimeter - An instrument such as the Klett-Summerson Industrial Model (for colorimetric analysis).

Variable Speed Shaker - Will Scientific Catalog No. 23690 with Box Carrier Catalog No. 23696.

Filter Paper - Whatman No. 3, Qualitative.

Spex-Mixer Mill - No. 8000 Spex-Mixer Mill and No. 8001 Grinding Vials, Spex Industries, Inc., 3880 Park Avenue, Metuchen, New Jersey.

B.4.2 Procedure

Grind a representative sample of carbon in a Spex-Miller Mill until 90 ± 5 percent will pass a 325 mesh screen (by wet screen analysis). Load the Spex-Mixer Mill with a 5.5 ± 0.5 gram sample and use 64 one-fourth inch diameter steel balls. An adequate sample of the carbon should then be dried at 140 degrees C for one (1) hour or 100 degrees C for three (3) hours.

Add 5.00 grams of pulverized carbon to a 250 ml Erlenmeyer flask (see Note 1). Add 80 ml of methylene blue solution (20 grams per liter) to the beaker. Shake at about 150 oscillations per minute for 20 minutes using a mechanical stirrer. Immediately after the stirring period, filter, through a Buchner funnel under vacuum, using Whatman No. 3 filter paper (see Note 2). Discard the first 10 to 15 ml of the sample filtrate and collect the remainder.

B.4.3 Colorimetric Analysis

Transfer the filtrate to a solution cell having a 40 mm effective depth and record the reading using a colorimeter with a green (540 mμ) color filter (see Note 4). Prepare a standard curve using methylene blue concentrations of 0.4, 1.0, 3.0, and 5.0 mg/l (see Note 3). Determine the concentration of methylene blue by reference to the standard curve (Table B-2). The methylene blue number is found by referring to Table B-3.

B.4.4 Notes on Procedure

1. The weight of sample taken is determined by the activity of the carbon. The 5.00 gram sample size is correct for carbons having methylene blue numbers ranging from 264 to 330. For carbons of higher activity, it will be necessary to use only a 4 gram sample while other carbons of lower activity will require from 6 to 8 grams to reduce the concentration of methylene blue in the filtrate reasonably close to that of the standards.

2. Prepare the filter beforehand by placing the filter paper in the funnel, wetting it thoroughly and removing excess water with the vacuum. Discard the water from the flask to prevent dilution of the test filtrate.

3. To prepare standards having methylene blue concentrations of 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0 and 5.0 mg per liter, dilute 5.0 ml of the 1.0 gram per liter methylene blue solution to one liter with distilled water. Then transfer 4, 6, 8, 19, 15, 20, 30, and 50 ml of the resulting solution to separate 50 ml volumetric flasks and dilute to 50 ml with distilled water.

4. If the filtrate color is deeper than a reading corresponding to 5 mg/l on the standard curve, pipette 0.5, 1, 5, or 10 ml into a 50 ml volumetric flask and dilute to the 50 ml mark with distilled water. Determine the methylene blue concentration for the diluted sample and use the following formula to determine filtrate concentrations:

$$\text{Filtrate concentration, mg/l} = \frac{\text{Diluted concentration} \times 50}{\text{ml sample pipetted into volumetric flask}}$$

TABLE B-2
DILUTION CHART FOR METHYLENE BLUE DETERMINATION

Methylene Blue Concentration, mg/l

Color Standard	No. of ml of Filtrate Taken				
	50 ml	10 ml	5 ml	1 ml	0.5 ml
3	0.4	2.0	4.0	20.0	40.0
3-1/2	0.5	2.5	5.0	25.0	50.0
4	0.6	3.0	6.0	30.0	60.0
4-1/2	0.7	3.5	7.0	35.0	70.0
5	0.8	4.0	8.0	40.0	80.0
5-1/2	0.9	4.5	9.0	45.0	90.0
6	1.0	5.0	10.0	50.0	100.0
6-1/2	1.25	6.25	12.5	62.5	125.0
7	1.50	7.5	15.0	75.0	150.0
7-1/2	1.75	8.75	17.5	87.5	175.0
8	2.00	10.0	20.0	100.0	200.0
8-1/2	2.50	12.5	25.0	125.0	250.0
9	3.00	15.0	30.0	150.0	300.0
9-1/2	4.00	20.0	40.0	200.0	400.0
10	5.00	25.0	50.0	250.0	500.0

TABLE B-3
METHYLENE BLUE CORRECTION CHART

(mg Methylene Blue adsorbed per gram of carbon at a filtrate concentration of 1.0 mg/l)

Methylene Blue Number

Filtrate Concentration mg Methylene Blue/l	Sample Size				
	4 gm	5 gm	6 gm	7 gm	8 gm
0.4	416	333	277	238	208
0.5	414	331	276	236	207
0.6	410	328	273	235	205
0.7	408	327	272	234	204
0.8	407	326	271	233	203
0.9	406	325	270	232	203
1.0	405	324	270	232	202
1.2	402	322	268	230	201
1.5	399	319	266	228	200
1.75	398	318	265	227	199
2.0	396	317	264	226	198
2.5	394	315	262	225	197
3.0	391	313	261	224	195
3.5	388	311	259	223	194
4.0	387	310	258	222	193
4.5	386	309	257	221	193
5.0	385	308	256	220	192
6.0	384	307	256	220	192
6.25	382	306	255	219	191
7.0	381	305	254	218	191
7.5	380	304	253	217	190
8.0	380	304	253	217	190
8.75	378	303	252	216	189
9.0	377	302	251	216	189
10.0	376	301	250	215	188

Methylene Blue Number

Filtration Concentration mg Methylene Blue/l	Sample Size				
	4 gm	5 gm	6 gm	7 gm	8 gm
12.5	374	299	250	213	187
15.0	371	297	248	212	185
17.5	370	296	247	212	185
20.0	368	295	246	211	184
25.0	365	292	243	209	184
30.0	363	291	242	208	182
35.0	361	289	241	207	181
40.0	360	288	240	206	180
45.0	358	287	239	205	179
50.0	357	286	238	204	179
60.0	355	284	237	204	178
62.0	353	283	236	203	177
70.0	352	282	235	202	176
75.0	351	281	234	201	175
80.0	351	281	234	201	175
87.5	350	280	233	200	175
90.0	350	280	233	200	175
100.0	348	279	232	199	174
125.0	346	277	231	198	173
150.0	344	275	229	197	172
175.0	342	274	228	196	171
200.0	341	273	227	195	170
250.0	338	271	226	194	169
300.0	336	269	224	192	168
400.0	332	266	222	190	166
500.0	330	264	220	188	165

B.5 Hardness Number (CWS)

A sample of carbon of a pre-selected mesh size is subjected to the action of steel balls on a Ro-Tap machine. The resistance of the carbon to degradation by this action is termed the Hardness Number.

B.5.1 Equipment

Ro-Tap - Sieve Shaker, Fisher Scientific Catalog No. 4-906.

Sieves - U. S. Standard Sieve Series, 8-inch diameter, full height sieves.

Hardness Testing Pan Assembly - See Figures B-2 and B-3.

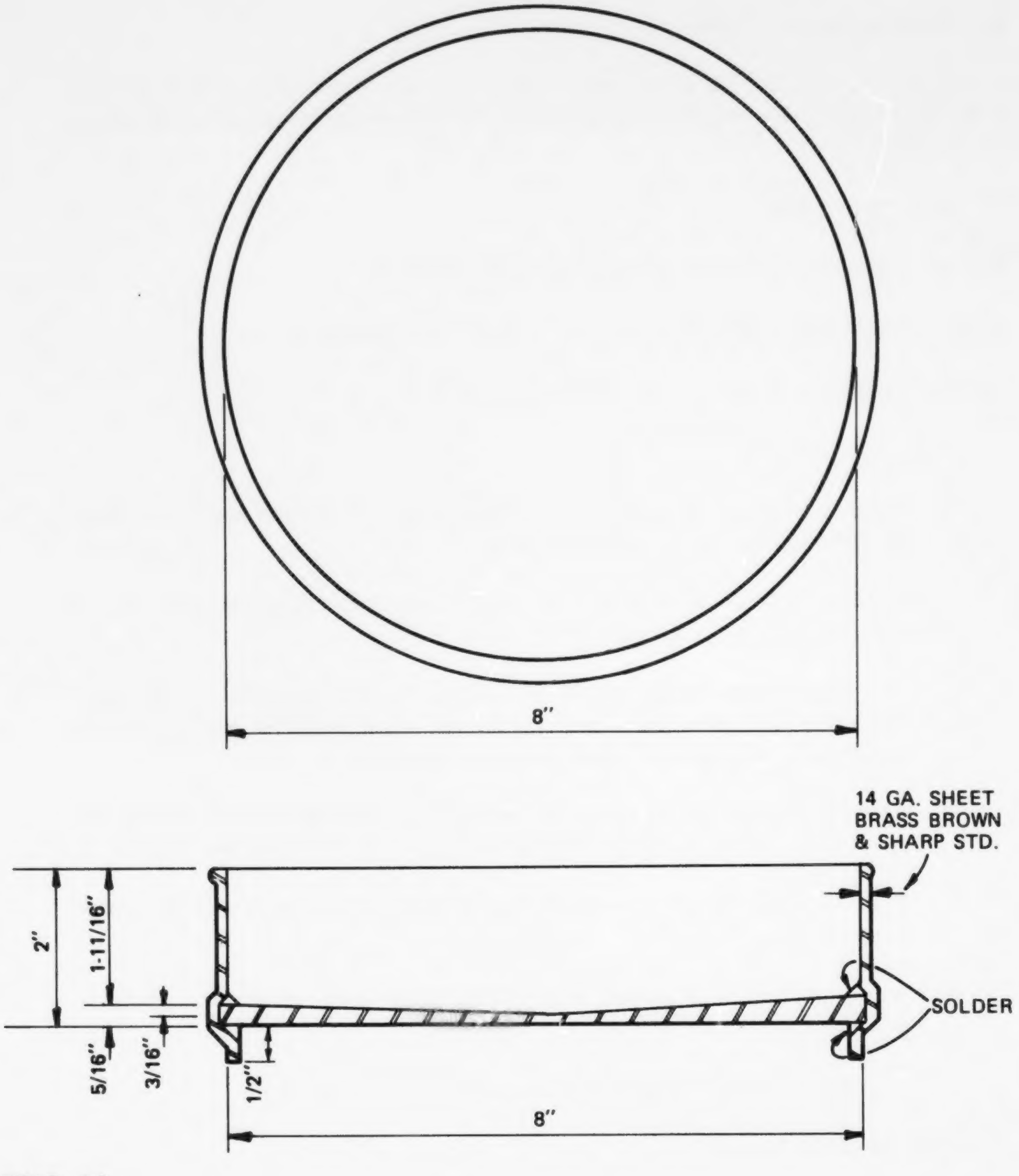
B.5.2 Procedure

1. Weigh 50.0 grams of prepared size material (see Note 1) and place in a special hardness testing pan (see attached figure).
2. Place 15 one-half-inch diameter and 15 three-eighth-inch diameter smooth steel balls in the hardness testing pan.
3. Nest the hardness testing pan with a bottom receiving pan below, a half-height blank pan and iron sieve cover above, and place assembly on the Ro-Tap machine for 30 minutes with the tapper in operation.
4. At the end of the 30-minute period, remove the steel balls on a No. 4 sieve and transfer the sample to a sieve nested on a bottom receiving pan (see Note 1).
5. Place the sieve assembly on the Ro-Tap machine for 3 minutes with the tapper in operation.
6. Weigh the material remaining on the sieve and calculate the Hardness Number as follows:

   Hardness No. = weight of material retained on sieve x 2

B.5.3 Notes on Method

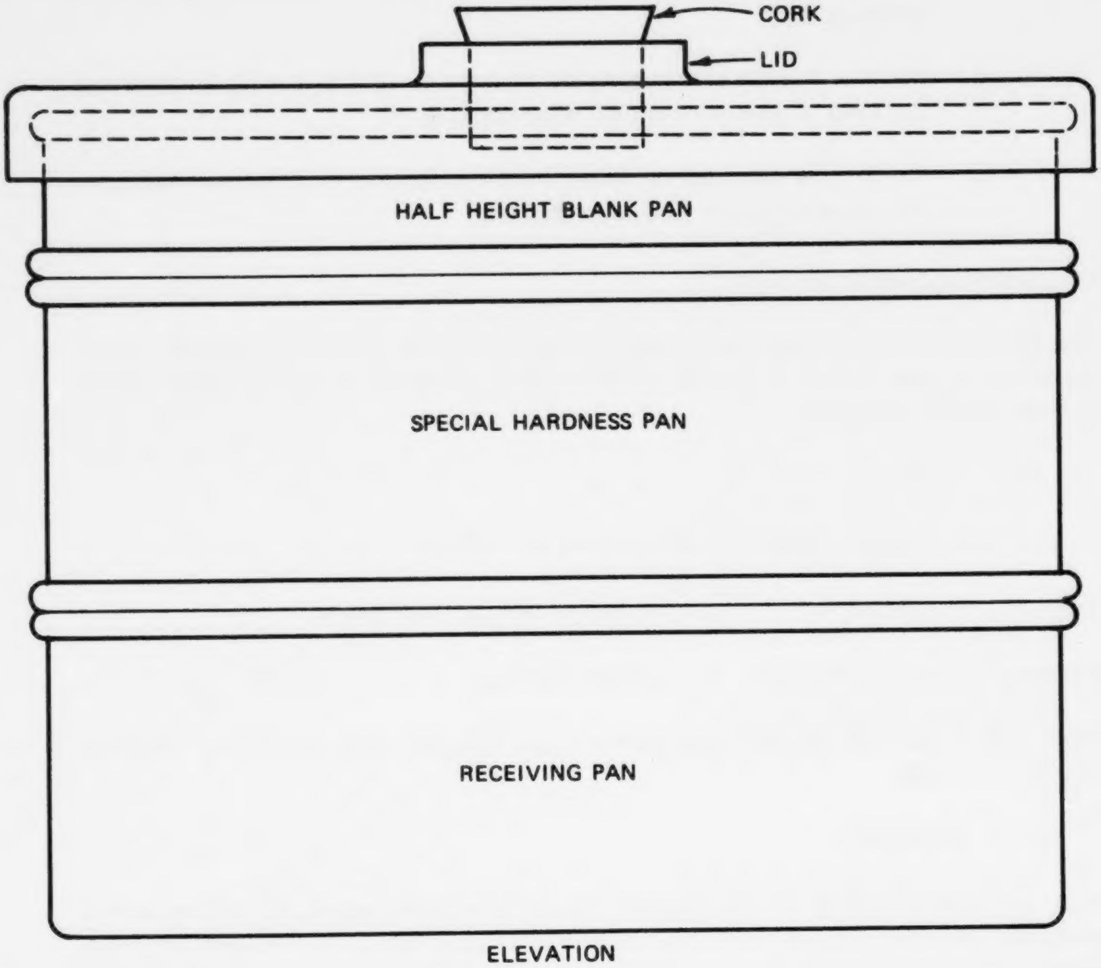
1. Selection of Special Sieve Sizes for Various Grades of Carbon
   a. For 4 x 8, 4 x 10, 6 x 8, 6 x 12 and 6 x 16 mesh carbons, prepare 50.0 grams of 6 x 8 mesh material by shaking approximately 100 grams of original sample for 3 minutes on a Ro-Tap machine, using the Nos. 6 and 8 sieves. Repeat, if necessary, until 50.0 grams are obtained. Use a No. 12 sieve for the final screening step.


8"
14 GA. SHEET
BRASS BROWN
& SHARP STD.
2"
1-11/16"
5/16"
3/16"
1/2"
SOLDER
8"

SCALE: 1:2

FIGURE B–2

TESTING PAN FOR DETERMINING HARDNESS AND ABRASION


CORK
LID
HALF HEIGHT BLANK PAN
SPECIAL HARDNESS PAN
RECEIVING PAN
ELEVATION

NO SCALE

FIGURE B–3

ARRANGEMENT OF ROTAP PANS
FOR HARDNESS AND ABRASION TEST

b. For 8 x 20, 8 x 30, 10 x 30, 12 x 30 and 12 x 40 mesh carbons, prepare 50.0 grams of 12 x 16 mesh material and use a No. 20 sieve for the final screening step.

c. For 4 x 6 mesh carbon, prepare 50.0 grams of 4 x 6 mesh material and use a No. 8 sieve for the final screening step.

d. For 8 x 14 mesh carbon, prepare 50.0 grams of 8 x 12 material and use a No. 16 sieve for the final screening step.

B.6 Abrasion Number (Ro-Tap)

The Abrasion Number of carbon defines the resistance of the particles to degradation by the action of steel balls in a Ro-Tap machine, and is calculated as the percentage change in mean particle diameter.

B.6.1 Equipment

Ro-Tap - Sieve Shaker, Fisher Scientific Catalog No. 4-906.

Sieves - U. S. Standard A. S. T. M. Sieves, 8-inch diameter, full height.

Hardness Testing Pan Assembly - See attached drawing.

Steel Balls - Ten (10) one-half-inch diameter and ten (10) three-quarter-inch diameter smooth steel balls.

B.6.2 Procedure

Make a dry sieve analysis of 100 grams of the material to be tested and save the screen fractions. The sieve analysis is to be done exactly as specified in the Westvaco Dry Sieve Analysis procedure except that the shaking time in the Ro-Tap is increased to ten (10) minutes. Sieves should be selected according to the nominal particle size of the carbon as set forth in attached Table B-4. Calculate the mean particle diameter of the sample from the sieve analysis (see Table B-5).

Recombine the fractions from the sieve analysis and place in the special hardness pan with 20 steel balls (see attached diagram of hardness pan and equipment list). Shake the pan assembly on the Ro-Tap machine for 20 minutes with the tapper in operation.

At the end of the 20 minutes, remove the steel balls, make another sieve analysis and calculate the mean particle diameter.

TABLE B–4

SUGGESTED SIEVES TO BE USED FOR SCREEN ANALYSIS

NOMINAL SIEVE SIZE	U.S.S. (N.B.S.) SIEVE NUMBERS
12 x 40	12, 16, 20, 30, 40, Pan
14 x 40	14, 16, 20, 30, 40, Pan
8 x 30	8, 12, 16, 20, 30 Pan
10 x 30	10, 12, 16, 20, 30 Pan
12 x 30	12, 16, 20, 30 Pan

TABLE B–5

FACTORS FOR CALCULATING MEAN PARTICLE DIAMETER*

U.S.S. SIEVE NUMBER	MEAN OPENING mm	U.S.S. SIEVE NUMBER	MEAN OPENING mm
+4	5.74		
4 x 6	4.06		
6 x 8	2.87		
		4 x 8	3.57
8 x 10	2.19		
10 x 12	1.84		
		8 x 12	2.03
12 x 14	1.55		
14 x 16	1.30		
		12 x 16	1.44
16 x 18	1.10		
		16 x 20	1.02
18 x 20	0.92		
20 x 25	0.78		
		20 x 30	0.72
25 x 30	0.65		
30 x 35	0.55		
		30 x 40	0.51
35 x 40	0.46		
40 x 45	0.39		
		40 x 50	0.36
45 x 50	0.33		
		50 x 60	0.27
50 x 70	0.25		
		60 x 70	0.23
70 x 80	0.19		
		70 x 100	0.18
80 x 100	0.16		

*The mean particle diameter of each fraction is assumed to be midway between the sieve opening in millimeters through which the material has passed and the sieve opening in millimeters on which the material was retained.

B.6.3 Calculations

$$\text{Abrasion Number} = \frac{\text{Final mean particle diameter}}{\text{Original mean particle diameter}} \times 100$$

The mean particle diameter of the whole sample is computed by multiplying the weight of the fraction by the respective mean sieve openings, summing these weighted values and dividing by total weight of material caught on the sieves and pan. The following example for a 12 x 30 mesh sample illustrates the method of calculation.

Sieve No.	Weight Retained On Sieve, g	Mean Opening mm	Weighted Average
On 12	1.5	2.03[a]	3.0
16	25.1	1.44	36.1
20	50.2	1.02	51.2
30	22.5	0.72	16.2
Pan	1.1	0.00[b]	0
	100.4		106.5

$$\text{Mean Particle Diameter} = \frac{106.5}{100.4} = 1.061 \text{ mm}$$

a. Assuming this material would pass the No. 8 sieve (or generally the next larger sieve in the square root of two series).

b. Material caught on the pan is not considered in calculating the Mean Particle Diameter.

B.7 Abrasion Number (NBS)

The apparatus consists essentially of an inverted T-shaped stirrer turning rapidly in a cylindrical vessel containing the activated carbon. The clearance at the ends of the stirrer and bottom are the only critical dimensions. The speed of the shaft is 855 ± 15 rpm. (Obtained with a 2:1 reduction by V belt from a 1,750 rpm motor 1/10 horsepower or larger). A simple frame for holding the drive motor and bearing container assembly is also required.

Procedure

1. Prepare a sample of activated carbon by the recommended sampling procedures having a volume of 250 to 300 ml.

2. Obtain a sieve analysis by the recommended sieving procedure. Discard the fractions through No. 70 sieve and recombine all sieve fractions coarser than No. 70 and place in hardness tester.

3. Operate the tester for 1 hour ± 1 minute.

4. Repeat the sieve analysis for the stirred mixture.

5. Calculate the percentage through No. 70 and record as the percent dust formation.

6. Calculate the average particle size, D, before and after stirring from the sieve analysis by means of the following relationship:

   $$D = \frac{\Sigma WiDi}{\Sigma Wi}$$

   where W is the weight of a sieve fraction, and the particle diameter, D, is obtained as the arithmetic average of opening of sieves above and below the fraction.

7. The percentage reduction in particle size is the decrease in average particle size calculated as a percentage of the original average particle size.

8. Since this test abrades particles in proportion to their size, divide both percentage reduction in particle size and percentage dust formation by particle size (in mm) before stirring in order to reduce both results to a standard 1 mm particle size.

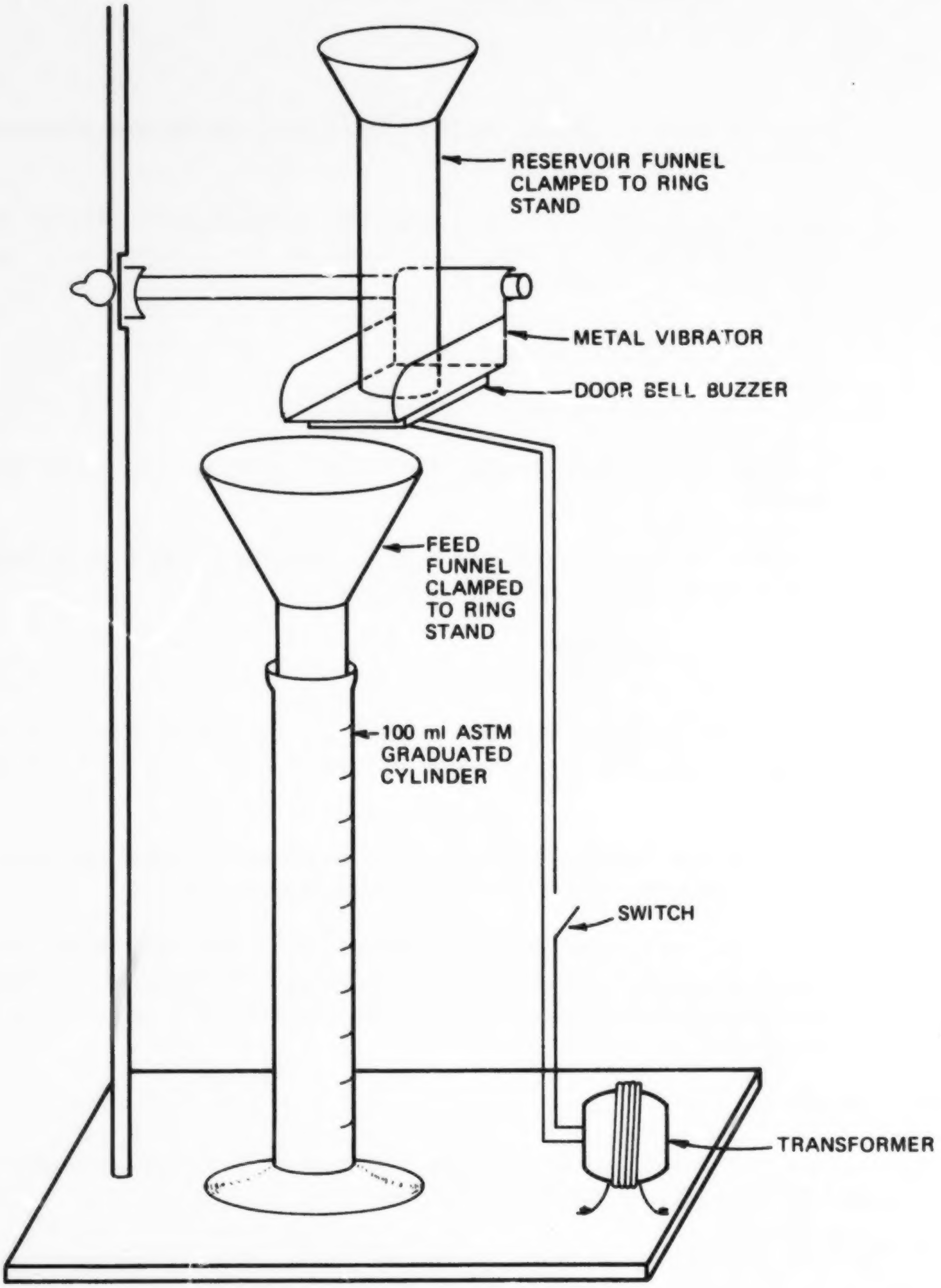
B.8 Apparent Density

The apparent density is defined as the weight of carbon per unit volume expressed in grams per cubic centimeter or pounds per cubic foot.

B.8.1 Equipment

Vibrator Feeder - See Figure B-4.

Cylinder - 100 ml A. S. T. M Graduated Cylinder


RESERVOIR FUNNEL CLAMPED TO RING STAND
METAL VIBRATOR
DOOR BELL BUZZER
FEED FUNNEL CLAMPED TO RING STAND
100 ml ASTM GRADUATED CYLINDER
SWITCH
TRANSFORMER

NO SCALE

FIGURE B–4

APPARENT DENSITY TEST APPARATUS

B.8.2 Procedure

Dry an adequate sample of the carbon to be tested at 140 degrees C for one (1) hour or 110 degrees C for three (3) hours. Place a representative sample of the dried carbon into the reservoir funnel of the apparent density apparatus. Material which flows prematurely into the graduated cylinder is returned to the reservoir funnel.

Fill the tared graduated cylinder to the 100 ml mark at a uniform rate so that filling time is not less than 100 seconds nor more than 133 seconds. The rate can be adjusted by changing the slope of the metal vibrator and/or raising or lowering the reservoir funnel. A powerstat can be used to regulate the speed of the vibrator, thus regulating the rate of filling of the cylinder. Determine the weight of the carbon in the graduated cylinder to the nearest tenth of a gram (0.1 gm).

B.8.3 Calculations

$$\text{Apparent Density, gm/cc} = \frac{\text{Weight of Activated Carbon}}{100}$$

B.8.4 Dimensions of Funnels and Vibrator

Metal Vibrator	1-3/4-inches wide
	3-1/2-inches long
	3/4-inch deep
Reservoir Funnel	Top diameter 3-inches
	Bottom Diameter 1-5/8-inches
	Overall height 4-inches
	Height to flared top 3-1/4-inches
Feed Funnel	Top Diameter 3-1/2-inches
	Bottom Diameter 15/16-inch
	Overall Height 4-inches
	Height to flared top 1-1/2-inches

B.9 Sieve Analysis (Dry)

The distribution of particle sizes in a given sample is obtained by mechanically shaking a weighed amount of material through a series of test sieves, and determining the quantity retained by or passing given sieves.

B.9.1 Equipment

Riffle, Jones Sample - Will Scientific Catalog No. L-23621

Ro-Tap - Sieve Shaker, Fisher Scientific Catalog, No. 4-906

Brush - For metal surfaces, brass wire bristle, Will Scientific Catalog No. 6916

Sieves - U. S. Standard A. S. T. M. Sieves, 8-inch diameter, full height.

Balance having a sensitivity of 0.1 gram.

B.9.2 Procedure

Reduce the sample to be tested to 100 grams by means of a riffle (see Note 1). Assemble the nest of desired sieves in order of decreasing size of opening, the sieve having the largest openings mounted on top. Place the 100.0 gram sample in the top sieve, install iron cover on top of the assembly and shake on the Ro-Tap machine for three (3) minutes with the tapper in operation (see Note 2). Weigh and report the percent of material retained on each sieve (see Notes 3 and 4).

Notes on Procedure

1. The sample is carefully reduced by repeated passes through the riffle until the amount collected on one of the riffle pans is close to 100 grams. The entire contents of that pan are then emptied onto a balance accurate to 0.1 gram and weighed. No more than 5 grams should be added to, or taken from, the balance without additional riffling. For example, if the entire contents from the riffle pan weighed only 90 grams, the additional 10 grams should be obtained by riffling another sample down to an approximate 10 gram portion, after which the entire contents of that riffle pan are emptied onto the balance. Removing large quantities from the balance or adding large quantities from the sample stock without riffling will lead to erroneous results.

2. When sieving samples which are finer than 100 mesh, the shaking time must be increased. Use 10 minute intervals until less than 2 grams are collected in the receiving pan in a 10 minute interval.

3. The sieve should be lightly brushed with a brass wire bristle brush to free particles held in the screen.

4. The analysis should be rejected if the sum of the individual fractions is less than 98.0 grams or more than 102.0 grams.

B.9.3 Sample Calculations

Sieve No.	Wt. Retained on Sieve, gms	% Retained
8	6.4	6.4
12	17.5	17.6
16	23.5	23.7
20	48.0	48.3
Pan	3.9	3.9
Total	99.3	

$$\% \text{ Retained} = \frac{\text{Weight Retained on Each Sieve}}{\text{Total Wt. Retained on all Sieves}} \times 100$$

B.10 Effective Size and Uniformity Coefficient

The Effective Size is defined as the size of the particle that is coarser than 10 percent, by weight, of the material. It is usually determined by the interpolation of a cumulative particle size distribution.

The Uniformity Coefficient is obtained by dividing the sieve opening in millimeters which will pass 60 percent of a sample by the sieve opening in millimeters which will pass 10 percent of the sample. These values are usually obtained by interpolation on a cumulative particle size distribution.

Procedure

1. Run a standard sieve analysis as outlined in the sieve analysis (dry) test procedure.

2. From the percentage retained on each sieve, the cumulative percent passing each sieve can be obtained (see Table B-6).

3. On probability x logarithmic paper, plot the sieve opening in millimeters on the ordinate, or vertical scale, versus the cumulative percent passing each sieve on the abscissa, or horizontal scale (see Figure B-5).

4. The Effective Size is determined as the millimeter opening at which 10 percent passes on the cumulative percent passing scale.

5. The Uniformity Coefficient is determined by dividing the millimeter opening at which 60 percent passes by the millimeter opening at which 10 percent passes.

TABLE B-6
EXAMPLE EFFECTIVE SIZE AND UNIFORMITY COEFFICIENT DETERMINATION

Sieve No.	Sieve Opening Millimeters	Wt. Retained on Sieve, grams	% Retained	Cumulative % Passing
12	1.680	0.3	0.3	99.7
16	1.190	20.7	20.9	78.8
20	0.840	49.4	49.8	29.0
30	0.590	22.0	22.2	6.8
40	0.420	6.5	6.6	0.2
Pan		0.2	0.2	
		99.1	100.0	

Effective Size: 0.66

Uniformity Coefficient: $\frac{1.04}{0.66} = 1.575$

B.11 Moisture

Moisture is the percent, by weight, of water adsorbed on activated carbon.

B.11.1 Procedure

1. Dry an aluminum moisture dish (2-inches in diameter by 7/8-inch deep) and lid in an electric oven for thirty (30) minutes at 110 degrees C. Cool in a desiccator and weigh.

2. Weigh approximately 2 grams of carbon into the tared dish, recording the exact weight.

3. Place the dish containing the carbon (lid opened to allow the moisture to escape) in the oven and allow to dry either three (3) hours at 110 degrees C, or two (2) hours at 140 degrees C. Close lid tightly, remove from the oven, cool the dish in a desiccator and weigh.

An alternate method is to use a moisture balance.

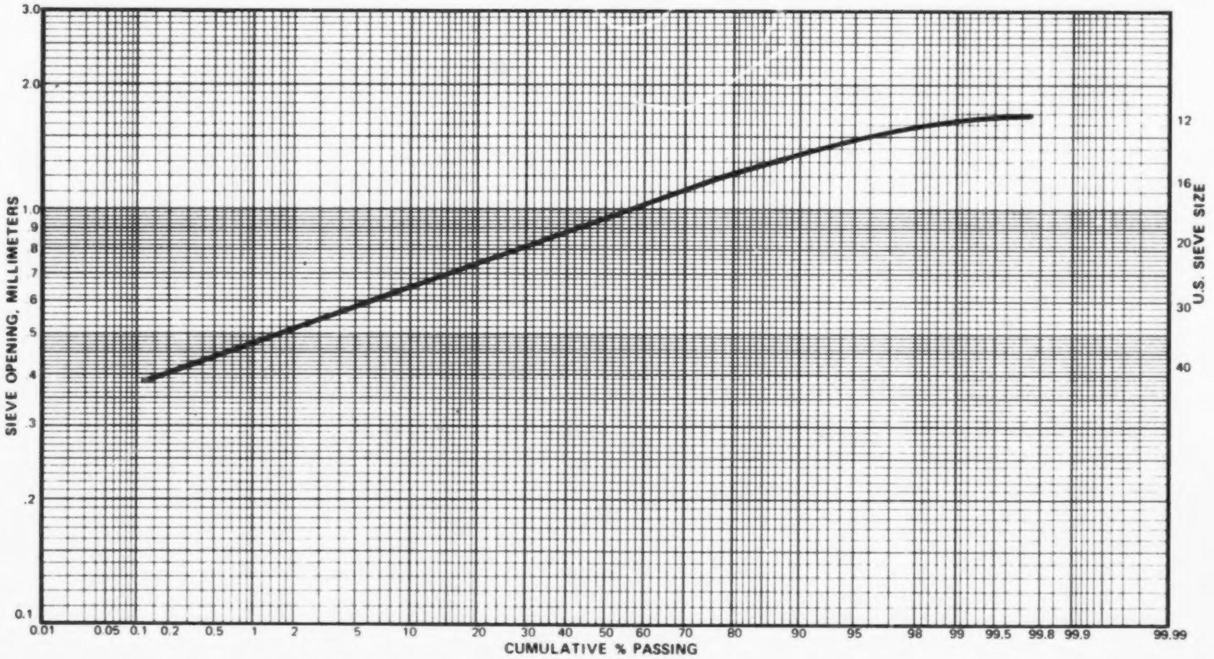


FIGURE B–5

CUMULATIVE PARTICLE SIZE DISTRIBUTION CURVE
(FOR DETERMINATION OF EFFECTIVE SIZE & UNIFORMITY COEFFICIENT)

B.11.2 Calculation

$$\text{Percent moisture} = \frac{\text{Loss in weight during drying}}{\text{Initial weight of sample}} \times 100$$

For example:

Weight of dish plus sample	=	15.5543
Weight of dish	=	13.5478
Weight of sample	=	2.0065
Weight of dish plus dried sample	=	15.4635
Loss of weight	=	.0908

$$\text{Percent Moisture} = \frac{.0908}{2.0065} \times 100 = 4.53\%$$

Values reported to the nearest 0.1 percent are satisfactory, i.e., in the above case, 4.5 percent.

B.12 Total Ash

The total ash of a carbon is a measure of the amount of the inorganic matter present. This test is accomplished by a combustion process in which organic matter is converted to carbon dioxide and water at a controlled temperature to prevent decomposition and volatilization of inorganic substances as much as is consistent with complete oxidation of organic matter.

B.12.1 Apparatus

Electric Furnace - Any type which can be controlled at 600 ± 25 degrees C.

Evaporating Dish - Shallow form, 80 mm diameter, 20 mm height.

Analytical Balance having a sensitivity of 0.1 mg.

Desiccator.

Oven, forced air circulation capable of temperature regulation between 100 and 150 degrees C.

B.12.2 Procedure

Heat an evaporating dish in an electrically heated furnace for thirty (30) minutes at 600 ± 25 degrees C, cool in a desiccator, and weigh. Weigh five (5) grams of the sample (dry weight basis) - dry at 110 degrees C for three (3) hours or 140 degrees C for one (1) hour into the tared dish, recording the exact weight of the dish and sample.

Ash the sample in the furnace at 600± 25 degrees C. The time required for complete ashing varies with the material being tested. Heating to constant weight assures complete ashing (leaving the sample in the furnace overnight will assure complete ashing). During ashing, the furnace door should be left slightly open to obtain an exchange of oxygen and gases. After ashing, cool the dish and sample in a desiccator and weigh.

B.13.3 Calculations

$$\text{\% Total Ash} = \frac{(\text{Wt. dish and ash}) - (\text{Wt. dish})}{\text{Dry weight of sample}} \times 100$$

APPENDIX C
METRIC CONVERSION CHART

Multiply	By	To Get
Inches	2.54	Centimeters
Feet	0.3048	Meters
Square Feet	0.0929	Square Meters
Cubic Feet	0.0283	Cubic Meters
Pounds	0.454	Kilograms
Gallons	3.79	Liters
Gallons/Minute	5.458	Cubic Meters/Day
Feet/Second	0.305	Meters/Second